AD-A033 831 NAVAL RESEARCH LAB WASHINGTON D C F/G 8/10

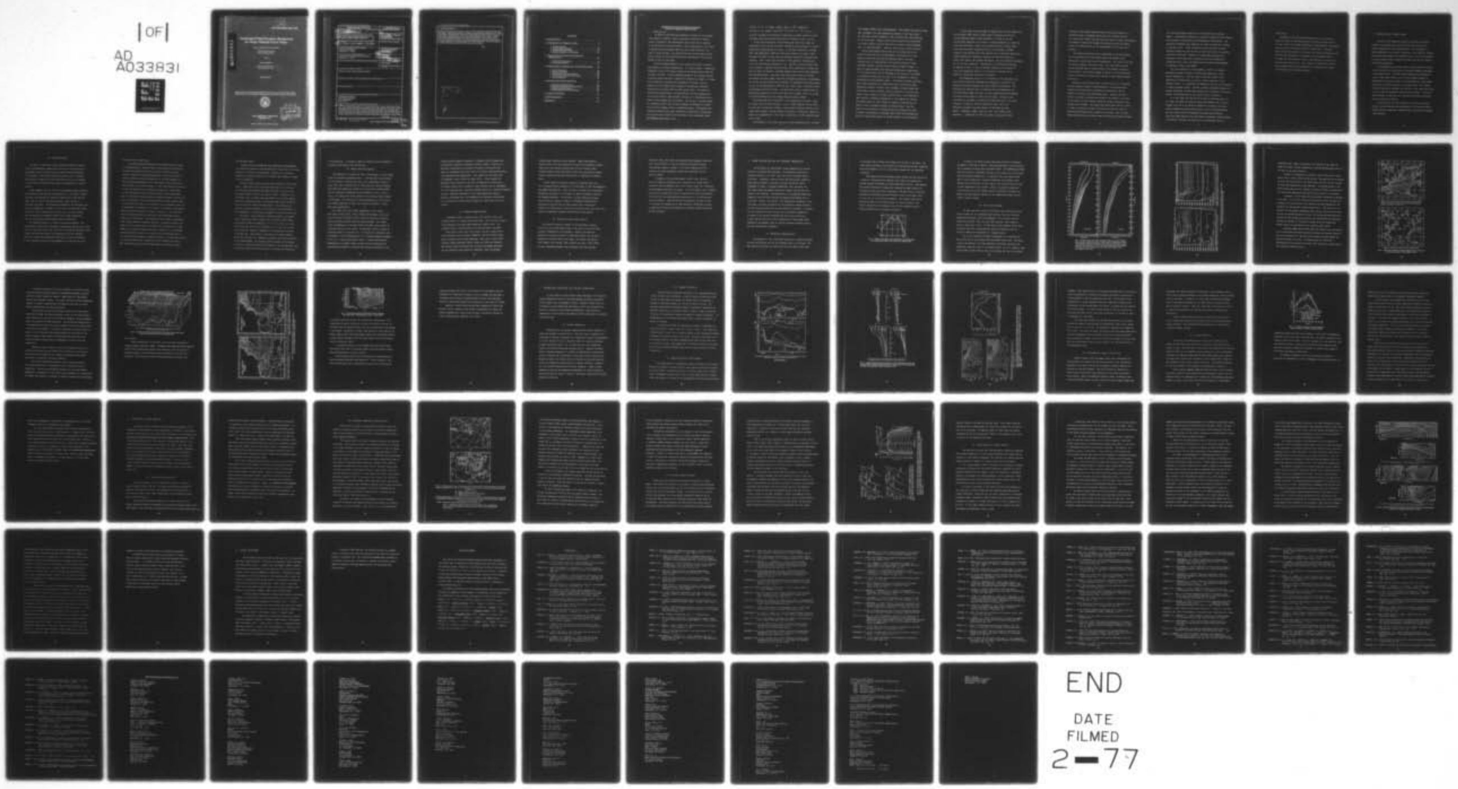
GEOPHYSICAL FLUID DYNAMICS BACKGROUND FOR OCEAN THERMAL POWER P--ETC(U)

OCT 76 S A PIACSEK, J TOOMRE, G O ROBERTS E(49-26)-1005

UNCLASSIFIED NRL-MR-3392 NL

1 OF 1

AD A033831



END

DATE FILMED

2-77

(12)
B.S.

NRL Memorandum Report 3392

Geophysical Fluid Dynamics Background for Ocean Thermal Power Plants

STEVE A. PIACSEK AND JURI TOOMRE

Plasma Dynamics Branch
Plasma Physics Division

and

GLYN O. ROBERTS

Science Applications, Inc.
McLean Virginia 22101

October 1976

Supported by the Ocean Thermal Energy Conversion Program, Division of Solar Energy, Energy Research and Development Administration, under ERDA contract E(49-26) 1005.

NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
14 -MR-
NRL [redacted] 3392

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
6 GEOPHYSICAL FLUID DYNAMICS BACKGROUND FOR OCEAN THERMAL POWER PLANTS.

5. TYPE OF REPORT & PERIOD COVERED
9 Interim report on a continuing NRL problem

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
10 Steve A. Piacsek, Juri Toomre [redacted] Glyn O. Roberts (SAI)

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Research Laboratory
Washington, D.C. 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
~~NRL Problem G01-16~~
15 E (49-26)-1005

11. CONTROLLING OFFICE NAME AND ADDRESS
Energy Research and Development Administration
Washington, D.C. 20545

12. REPORT DATE
11 Oct[redacted]76

13. NUMBER OF PAGES
77 12 69p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Geophysical fluid dynamics
Ocean thermal power plant
Environmental impact
Plant efficiency

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The vertical temperature gradient in the tropical oceans can be used to operate ocean thermal power plants (OTPP's) that function as heat engines. Such energy extraction would entail very large scale pumping of both warm surface water and cold bottom water through heat exchangers, with consequent disturbance and extensive mixing of surface and deep waters. The temperature difference between the warm and cold inflow water should be maximized for plant efficiency, but entrainment and recirculation between the inflow and the outflow may reduce this temperature contrast. Further,

(Continued on p. ii)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

251 950
bpg

20. Abstract (Continued)

horizontal currents and turbulence carry the outflow water to large distances and may produce significant changes. These flows are crucial in determining the thermal resource availability and the environmental impact of OTPP operation. This report provides background material and brief assessments in several areas of geophysical fluid dynamics (GFD) that bear directly on these problems. Relevant GFD research areas discussed include: turbulence and thermal wakes; ocean circulation and the permanent thermocline; air-sea interaction and thermocline variation; weather and climate modeling; and marine ecosystems. The report illustrates how each GFD area relates to specific OTPP problems, and emphasizes the multiple disciplines in GFD that must be considered.

CONTENTS

GEOPHYSICAL FLUID DYNAMICS BACKGROUND FOR OCEAN THERMAL POWER PLANTS

1. INTRODUCTION

We begin by outlining some fundamental features of ocean thermal power plants (or OTPP's). Next we describe the problems of thermal resource availability and environmental impact which can be expected in the operation of such power plants. Then we introduce the five areas of geophysical fluid dynamics (GFD) that have direct bearing on the study of these problems. The remaining sections of this report provide partial surveys of the literature and brief assessments of the research methods in the five GFD areas.

Vertical thermal gradients in the oceans can be used to operate heat engines of various configurations. In tropical waters, a temperature difference of about 20°C exists between the sun-warmed surface water and the deep cold water. The more advanced designs of heat engines intended to extract energy from such a temperature difference are based on a closed cycle, employing a working fluid like ammonia or propane. Heat is supplied to the working fluid by passing it through heat exchangers (evaporators) in contact with the warm surface water. This serves to vaporize the working fluid, at a high pressure; the high pressure gas can be used to drive a power turbine, provided it is recondensed at low pressure upon emerging from the turbine. The cooling of the gas leading to condensation would occur in heat exchangers (condensers) in contact with cold water pumped up from a considerable depth. The working fluid continually repeats this cycle, effectively transferring a considerable flux of heat from the warm to the cold water, while converting a small

Note: Manuscript submitted October 7, 1976.

portion of it to usable energy. With a $20^{\circ}C$ temperature difference, the maximum theoretical efficiency of a heat engine is about 7 percent, but allowing for losses and for power required to drive the pumps, the practical efficiency would lie between 0.5 and 2 percent.

At such low efficiencies, ocean thermal power plants must pump vast quantities of both warm and cold water through the heat exchangers to produce commercially viable amounts of energy. At 2 percent efficiency, a 500 MWe OTPP must pump nearly 2000 cubic meters per second (or of order 1 cubic kilometer per week) of both warm and cold water through its evaporator and condenser. Such a large scale movement of water masses is characteristic of all the OTPP designs considered so far. The OTPP in several design forms can be viewed as a massive cold water pipe, 300 to 1000 meters in length and about 40 meters in diameter, extending downward from the main plant submerged near the warm surface. The plant, with further water inlets and outlets, accommodates the water pumps, large heat exchanging evaporators and condensers, and electricity generating turbine machinery. To supplement this brief summary, we refer to the discussions of OTPP's by Lavi (1973), Zener (1973a,1973b,1974), and Heronemus (1973,1974a,1974b). The most recent design considerations and engineering evaluations of OTPP's are summarized in Dugger (1975), an outcome of the Third Workshop on Ocean Thermal Energy Conversion (OTEC).

Such power generation using OTPP's is environmentally attractive. Since the energy source is solar heating, it is not readily depleted. Nor is there any fuel cost or radioactive danger or waste disposal problem. Effects on the climate and on marine life may perhaps be tolerable or beneficial, though this remains to be demonstrated. The technical feasibility of OTPP operation seems close at hand.

The problems at first sight are mostly in the engineering area, concerned

with design, capital cost, and maintenance. They include the need for cheap heat exchangers, the ocean engineering problems of cold water pipes and anchoring, energy transmission from a floating OTPP, and biofouling of the flow system. However, quite crucial questions are raised about the thermal gradient resource availability and about the environmental impact of operating OTPP's. These two areas require careful attention.

Though ocean thermal power plants are not accompanied by the ejection of net heat into the environment, the extraction of large amounts of heat from localized and extended areas of the upper ocean may lead to a perturbation in the delicate balance of ocean-atmosphere dynamics, causing possible regional climatic changes. A group of operating OTPP's will erode the thermocline in large areas of the tropical ocean, and the knowledge of its recovery to a previous or permanently altered state is vital to the assessment of resource availability and environmental impact. To maintain efficient operation, OTPP's must be operated in a thermocline with a sufficiently large temperature contrast, the exact value depending on engine design and power output. Hence, they must either be anchored in a current, presumably close to shore or in fairly shallow water, or be propelled at some velocity to maintain availability of this temperature contrast. The spatial extent of their "wakes" or regions of influence must be known in order to minimize interaction between plants. The time scales of the recovery of a thermocline must be understood in order to prevent the propelled or "grazing" kind of OTPP from returning too soon to an ocean region where the thermal gradient is still depleted.

In this report we will attempt to identify the role that geophysical fluid dynamics (GFD) plays in these issues of resource availability and environmental impact of OTPP operation. In doing so, we will provide brief summaries of the status of research progress in a selection of relevant GFD areas. These are certainly difficult research areas, since even the simpler formulations tend to be nonlinear. Further, progress in GFD research has often resulted from a complicated interaction between observation, experiment, analysis and numerical simulation. Clearly also some of the relevant GFD aspects, such as stratified turbulence, are not yet well understood. Nevertheless, the techniques of GFD must be employed if one is to obtain realistic estimates of the effects of large scale pumping by OTPP's or of how natural variations can be expected to modify the efficiency of operation.

The fundamental need is for a calculation of the near-plant flow, which would provide mean disturbances of temperature, salinity, and biological nutrients, together with their turbulent fluctuations. The calculation is required first to determine the mean temperatures for both OTPP inflows (warm and cold), as these temperatures may be modified by possible recirculation of water near the plant. Secondly, this caluclation is necessary to determine the OTPP impact from a far-field viewpoint, in terms of vertical transport of heat, salt, and biological nutrients. Detailed research on OTPP wakes has been minimal. McMichael (Zener, 1974, pp. 8-16) and Trimble (1975, Appendix P) suggest that an OTPP can operate continously without

spoiling its own thermal gradient resource even when anchored in a stationary ocean. We suggest instead that the turbulent outflow will recirculate locally, and thus ruin the resource; careful calculations are needed to identify the maximum OTPP pumping rate and the minimal motion of an OTPP relative to its surroundings to avoid this recirculation.

The turbulent near-plant flow is determined by the OTPP inflows and jet outflows, by the plant design, and by the ambient ocean temperature, salinity and current distributions. This kind of flow has not been successfully predicted to date. But some closely related studies have been made on thermal wakes in the presence of density stratification. We therefore present in section 2 a brief background review of this work, as specifically related to ocean thermal energy conversion.

Studies of the far-field effect of OTPP operation on the thermal gradient resource require an understanding of the processes which maintain the average vertical temperature distribution, and its seasonal variation, in the undisturbed ocean. Briefly, the ocean surface is cooled at the poles and warmed in the tropics, as a result of the balance of solar heating, infra-red cooling, evaporation, and sensible heat transfer. The cooled polar water sinks, and as a result of deep circulation the ocean is filled with cold water, with an overlaying warm buoyant layer (except at the poles). Heat is transferred poleward from this surface layer by wind-driven surface currents,

and vertically downward (against the stratification) by turbulent mixing. A weak general upwelling of cold water outside the polar regions then maintains a statistically steady temperature distribution. The geophysical background and literature for these processes are outlined in sections 3 and 4. There we deal with ocean circulation and the permanent thermocline, and also with air-sea interactions that produce thermocline variations. Clearly it is these same processes which determine the far-field rate of recovery of the ocean towards its undisturbed state, after the thermal stratification has been modified by operation of one or more OTPP's.

Also, the operation of a large number of OTPP's in a limited geographical region is likely to produce some reduction in ocean surface temperatures. This may cause a sufficient change in air temperature and evaporation to produce a slight alteration in the regional climate. It is important to demonstrate that any such alteration is within acceptable limits. Section 5 presents background material on weather prediction methods using limited area and general circulation models, and discusses some of the results related to climate.

It is well known that marine life thrives in upwelling regions of the ocean, and these are among the worlds best fishing areas. This is thought to be due to the vertical transport of biological nutrients, mainly phosphate and nitrate, which support plant life (phytoplankton) and thus provide food for zooplankton and larger marine animals. Large scale OTPP operation will also produce substantial upward transport of biological nutrients, and thus may be of considerable value in

mariculture.

Assessment of the detailed biological impact of a particular region and scale of OTPP operation will require a detailed model of the way in which the present distribution of phytoplankton, zooplankton, detritus, fish and dissolved nutrient is maintained. This model should include the effects of horizontal and vertical transport by the mean flow and turbulence, the dependence of phytoplankton growth on light, and the sinking of detritus which depletes the nutrient in the insolated surface layer. Such a model is discussed in section 6, which provides the necessary background for determining the impact of OTPP operation on the marine ecology.

2. TURBULENCE AND THERMAL WAKES

The flow in the immediate vicinity of an OTPP is turbulent because of the outflow jets, the flow round the plant, and the buoyant adjustment of the diffused outflow. This turbulence is three-dimensional, and its study constitutes a very difficult problem. Related previous research has concerned two main areas, the dispersal of heated effluent from a conventional power plant and the turbulent wakes behind submarines.

In determining the far-field impact of OTPP operation, we need to know the vertical distribution of turbulent transport properties in the ambient ocean. The OTPP induced turbulence has decayed to zero at these large distances, but the OTPP induced changes in temperature and salinity remain, and are modified over long periods by vertical turbulent diffusion in the mixed layer. The relevant diffusivities must be obtained from studies of this ocean mixed layer or of the similar atmospheric boundary layer problem. In either of these studies, the mean flow and turbulence properties vary mainly with the vertical coordinate.

In this section, we first describe the different turbulence models, and then discuss their application to the three problems of thermal effluent dispersion, submarine wakes, and planetary boundary layer modeling.

(a) *Turbulence Models*

The study of turbulence, and the practical modeling of complicated three-dimensional random flows, is still in an early stage of development, and constitutes one of the major unsolved problems of fluid dynamics. Four distinct methods have been used in studying these flows; of these four we feel that only two can yet be applied to OTPP flows at reasonable cost and with reasonable hope of partial success.

First, Orszag (1972 a,b, 1973 a,b) has computed certain turbulent flows exactly, using numerical representations of the Navier - Stokes equations, and resolving all length and time-scales in the inertial range, down to those of the smallest eddies, where viscosity dissipates the energy. The statistical averages of the resulting flows should be independent of changes in the initial conditions and in the resolution. Such calculations are restricted by cost and computer size to relatively low Reynolds numbers and to simple geometries; they are a long way from being practicable for OTPP flows.

The remaining methods all involve closure approximations. The second method is the direct interaction approximation and the test field models of Kraichnan (1959, 1971, 1973) and of Herring and Kraichnan (1971). These have given good results for homogeneous isotropic problems and even in some more complicated situations, and have the advantage of not requiring a choice of free parameters, but they are too costly

for application to OTPP flows.

The third and fourth methods for calculating turbulent flows are phenomenological, and both involve splitting the flow variables into mean and perturbation parts, with only statistical average products computed for the perturbation parts. The third method is *sub-grid closure,* in which the mean part of the flow variables is their smoothed representation on a coarse mesh, which resolves only the beginning of the inertial range. In the fourth method, *statistical closure,* the mean flow is the ensemble average over a large number of flow realizations, and is therefore steady in many applications. Both of these closure methods include turbulent transport terms in the mean flow equations. These terms are modeled in three different ways: *in eddy diffusivity models,* the turbulent fluxes of momentum, heat, etc. are determined from gradients of the mean flow variables, using imposed eddy diffusivities (possibly functions of position). In *first-order models* the diffusivities are calculated from the turbulent kinetic energy and a length scale. The turbulent kinetic energy is determined from a partly empirical transport equation. In sub-grid closure, the length scale is proportional to the mesh size; in statistical closure models it is either an imposed function of position, or is calculated algebraically from the mean flow variables and their derivatives, or is computed from an empirical transport equation. In *second-order models,* the various turbulent flux components are each computed from transport equations; these equations involve empirical generation, decay,

and diffusion terms.

Clearly both the sub-grid and the statistical closure methods are essentially empirical, and can become very complicated, with large numbers of constants to be determined. Hopefully such constants would have universal validity, but it appears that changes are needed for each simulation.

Sub-grid closure models are discussed by Deardorff (1967, 1970, 1974). These models are always three-dimensional, since the mean flow variables must describe the random turbulent fluctuations for the longest length scales in the inertial range. Depending on the resolution, they can range from being similar to the fourth method, right up to being equivalent to the second method (with the mesh so fine that sub-grid effects are negligible). The results can be validated either by agreement of the statistics with observation, or by convergence of the statistical averages with improving resolution.

Statistical closure models are discussed by Mellor and Yamada (1974), Stuhmiller (1975), Launder (1975), Biringen (1975), Vager and Zilintin (1968) and Lewellen et al. (1973 a,b, 1974 a,b). The statistical mean flow can be a function of zero, one, two or three space variables, ranging in complexity from homogeneous turbulence to an OTPP flow. Some variant of the statistical models probably offers the best hope for a reasonably economical and accurate solution for the OTPP problem. The uncertain question appears to be whether a realistic turbulent diffusivity distribution (or the equivalent with second-order closure) will be sufficient to suppress the instability

of the mean flow. If stability cannot be insured, the more expensive sub-grid closure method will be necessary.

(b) Thermal Effluent Dispersal

The dispersal of cooling water from a conventional or nuclear power plant has received considerable study. A 500 Mwe plant produces about 2×10^8 cal/sec of effluent heat flux, with a temperature excess of about 20°C, and a volume flux of 10 cubic meters per second (compared with 2000 cubic meters per second for our illustrative 500 Mwe OTPP). We are interested in submerged outlets (whether it be in a river, a lake, or an ocean) since these situations are the most closely related to OTPP wakes. The influences of bottom topography and of the shoreline should preferably be weak, since these are unlikely to affect OTPP wakes significantly.

Fan (1967), Koh & Fan (1970), Baumgartner & Trent (1970), Policastro & Tokar (1972), Jirka, Abraham and Harlemann (1975), and Dunn, Policastro and Paddock (1975) have given extensive literature surveys and model studies concerning these problems. Ahn & Smith (1972) and Mangarella & Van Dusen (1973) have made recent studies related specifically to the oceans. The important effects, roughly in increasing order of time-scale are: a) turbulent jet formation, with entrainment of cool surrounding water; b) turbulent buoyancy adjustment of the jet to find its own density level; c) laminar gravitational broadening of the thermal plume; d) near-surface fluctations with time-of-day and weather; e) vertical and horizontal diffusion of the

thermal plume by ambient turbulence; f) seasonal surface changes; and g) horizontal advection to different climatic regions. There is considerable uncertainty in the theoretical models, particularly with regard to turbulence, and a great need for detailed comparison with data from experiments and observations. Data compilations have been made by Silberman & Stefan (1970) and Tokar (1971). Jirka, Abraham and Harlemann (1975) conclude on the basis of comparison of observations with model results that the models in their present state of development are still unsatisfactory. The main problems concern the turbulence representations, numerical convergence of the three-dimensional computer models at reasonable cost, the complexity and consequent inflexibility of the codes, and the wide range of length and time-scales to be considered.

(c) Turbulent Submarine Wakes

A submarine leaves a turbulent wake, which entrains fluid from different levels in a density stratified ocean. The resulting collapse and broadening of the mixed region generates internal waves. The turbulent wake is closely related to the jets and wake of an OTPP.

Miles (1971), Gran (1973), Bell (1973), and Bell & Dugan (1973) have considered the flow around a submarine, and the lee waves (body waves, internal gravity waves) generated. Chan, Hirt & Young (1972), Lewellen, Teske & Donaldson (1973a, 1974b), Ko (1973) and Piacsek & Warn-Varnas (1975) have modeled the turbulent entrainment processes and the turbulence decay behind the submarine, using increasingly

sophisticated turbulence closure methods. Dugan, Warn-Varnas & Piacsek (1973, 1974) have studied the internal wave generation process numerically with uniform stratification and no horizontal shear. Piacsek & Roberts (1975) and Roberts (1975) have successfully treated general density and velocity distributions in computing the internal waves.

A great simplification which applies to submarine wakes, but not to thermal effluent dispersal or to OTPP wakes, is the "two-dimensions plus time" approximation. Since the wake is slender and the streamwise derivatives are small, it is possible to neglect streamwise diffusion and pressure gradients. The problem is further simplified because the flow does not separate around the streamlined submarine body; separation is certain with the OTPP designs under consideration. Probably for these reasons, statistical turbulence models have given wake results in reasonable agreement with laboratory measurements.

(d) Planetary Boundary Layer Modeling

The vertical turbulent transport in the atmospheric boundary layer and in the surface mixed layer of the ocean is one of the major problems of geophysical fluid dynamics. Analytic and numerical modeling by statistical methods is simplified because only one space dimension is involved (Mellor and Yamada, 1974; Mellor and Durbin, 1975; Yamada, 1975; Launder, 1975; Lewellen and Teske, 1973b, 1974a) and some reasonable agreement with experiments has been obtained.

Deardorff (1967, 1970, 1974) has obtained better agreement using sub-grid closure models, but this has involved considerably greater computational expense. Orszag & Pao (1973) simulated the full equations for three dimensional shear-layer turbulence, at low Reynolds number.

In regard to the far-field impact of OTPP flows, the same vertical turbulent diffusivity which influences the natural distributions of heat and momentum (and in the ocean of salt) also influences the disturbance produced by the plant. It may be cheaper, and of adequate accuracy, to calculate the vertical turbulent diffusivity distributions as the ratio of the observed mean turbulent flux to the observed mean vertical gradient. These diffusivity distributions can then be used to calculate the changes due to OTPP operation, eliminating any need to compute diffusivities corresponding to different weather conditions and wind stresses.

3. OCEAN CIRCULATION AND THE PERMANENT THERMOCLINE

The existence of a sufficiently strong thermocline is a prerequisite of successful OTPP operation. The thermocline represents a transition region in the ocean, where the density increases rapidly with depth. In general a density profile may show several regions of large density gradients, including a diurnal thermocline (which disappears at night), a seasonal thermocline, and a permanent one. Ater large storms new gradient regions may appear, and old ones disappear or get displaced. The maintenance of the permanent thermocline depends on both the ocean currents and turbulent entrainment due to the global, climatic wind systems. The time-varying components, on the other hand, are mostly determined by the atmospheric weather patterns and solar heating through the air-sea interaction processes. In section 3 we will discuss the ocean currents and the permanent thermocline, in section 4, the variable components and the air-sea interaction. In each case, we will give a brief introduction to the present understanding of the dynamics, some of the more successful modeling efforts, and some observational highlights.

(a) Thermocline Characteristics

The permanent or main thermocline represents a transition between the warm surface water and the cold "abyssal water" of the ocean. The deep layers of the ocean are filled with very cold water, which sank

at the poles, and is rising very slowly over the rest of the ocean. The upper layers are warmed at the surface by solar heating and heat conduction from the atmosphere, and this heat diffuses downward by wind generated turbulence.

This *upwelling* has an estimated global average vertical velocity of 2 cm/day or 7 meters per year (Wyrtki, 1961) which just balances the average downward entrainment by storm-driven eddy diffusion. The seasonal and spatial variations in thermocline thickness and depth reflect the variations of wind and surface temperature, and their effect on the eddy diffusivity distribution and the horizontal fluxes in the upper layer, in a way that is not yet fully understood. The latitude variation of thermocline depth in the Atlantic Ocean is shown in Figure 1; the shallow thermocline at the equator is due to the combined effects of strong upwelling and low turbulent diffusivity.

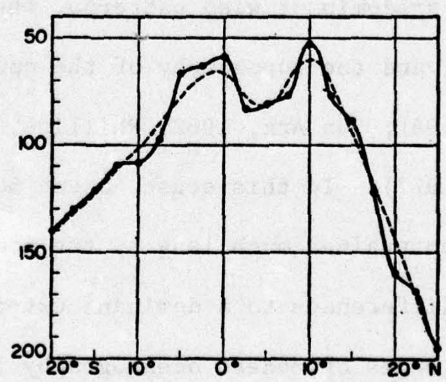


Fig. 1 — Variation of the depth of the thermocline in the Atlantic Ocean with latitude (mean values for the entire ocean) [Defant, 1961]

In Figure 2 are shown average temperature profiles for February and August in the Gulf of Mexico. These representative tropical profiles show a seasonal variation above 350 meters depth. The temperature profile below this depth is reasonably invariant to the season, and is associated with the permanent thermocline. In regions of the ocean where strong warm or cold currents flow, the main thermocline will exhibit a much sharper spatial variation; in some cases it will coincide with the lower or upper boundaries of the current. Figure 3 represents temperature cross sections in the Gulf Stream, again in the months of February and August; the rapid spatial variation of the temperature between 500 and 1200m is clearly visible.

(b) Ocean Current Systems

The most important factors in determining the circulation of the world's oceans are the predominant wind patterns, the pole to equator temperature difference, and the topography of the continents and the ocean bottom (Defant, 1961; Von Arx, 1962; Phillips, 1966; Neumann & Pierson, 1966; Kraus, 1972). In this sense, ocean movements differ from the winds, which are constrained much less by the mountains and are driven by temperature differences to a dominant extent.

One of the challenges of modern oceanography is to separate the wind driven part of the currents from the density driven part. The depth to which the effects of the wind penetrates is limited, and except for topography, could not couple to the deeper layers. As it is, however, wind-driven surface fluxes interact with the continents and lead to well-known

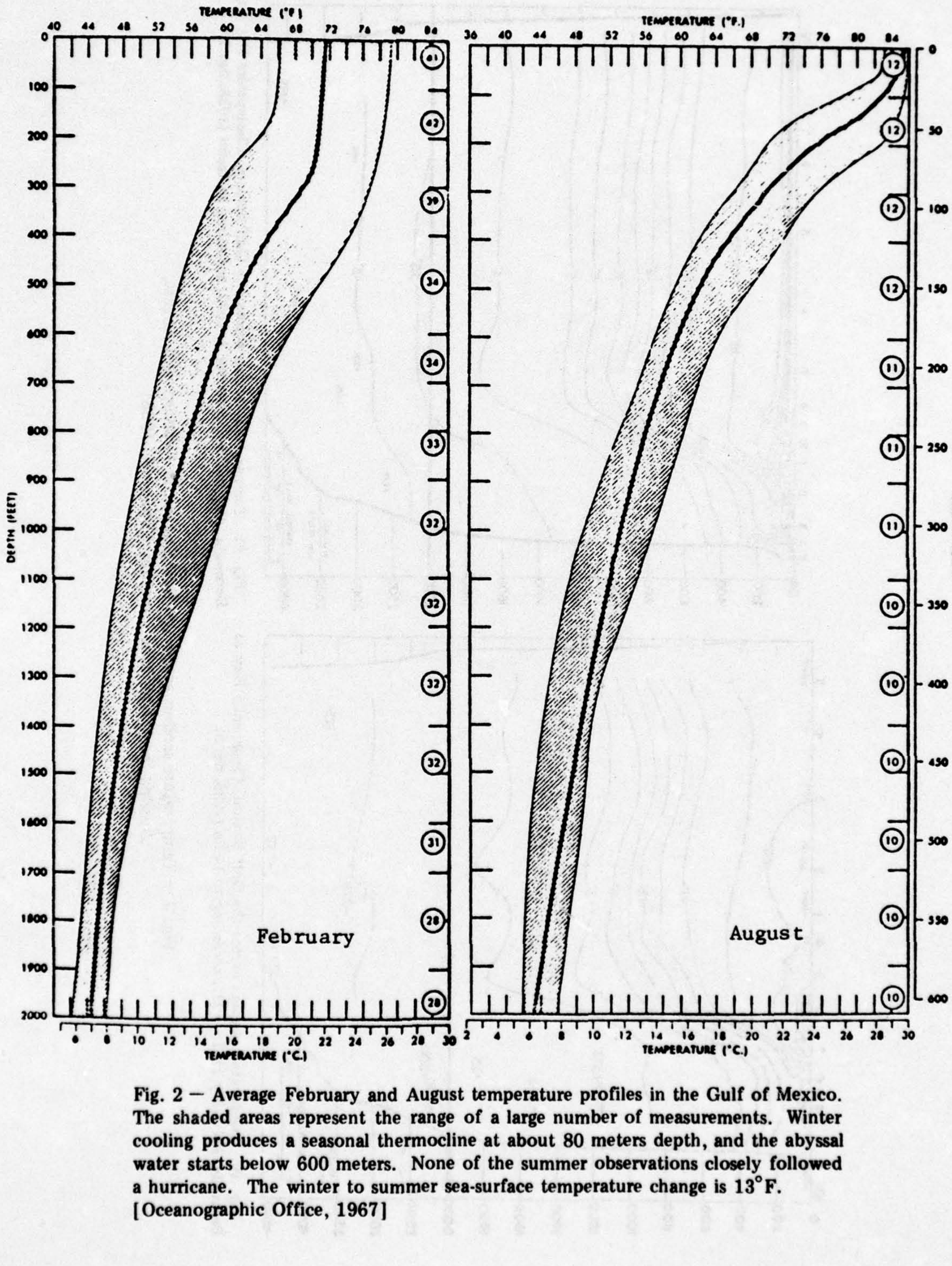


Fig. 2 — Average February and August temperature profiles in the Gulf of Mexico. The shaded areas represent the range of a large number of measurements. Winter cooling produces a seasonal thermocline at about 80 meters depth, and the abyssal water starts below 600 meters. None of the summer observations closely followed a hurricane. The winter to summer sea-surface temperature change is 13°F. [Oceanographic Office, 1967]

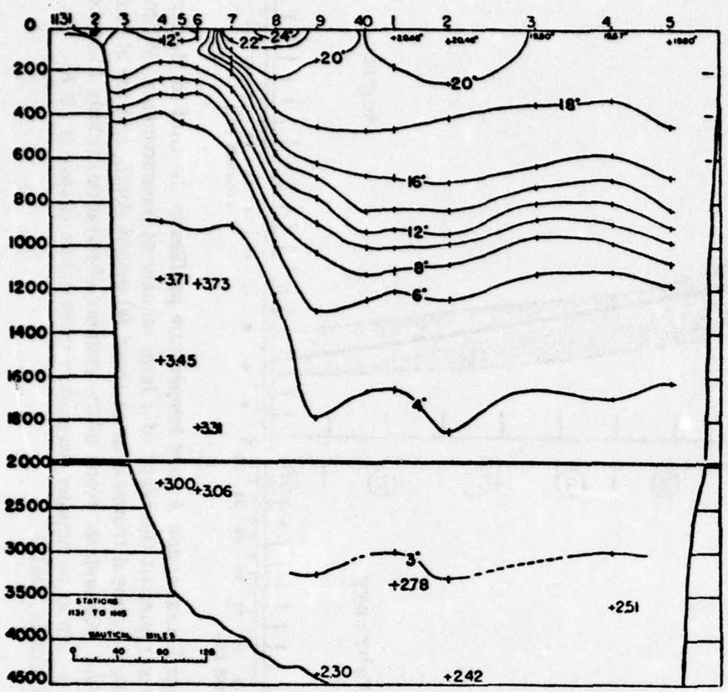


Fig. 19. Temperature section across the Gulf Stream, Chesapeake Bay to Bermuda, February 11–18, 1932, according to Iselin (1936, fig. 3).

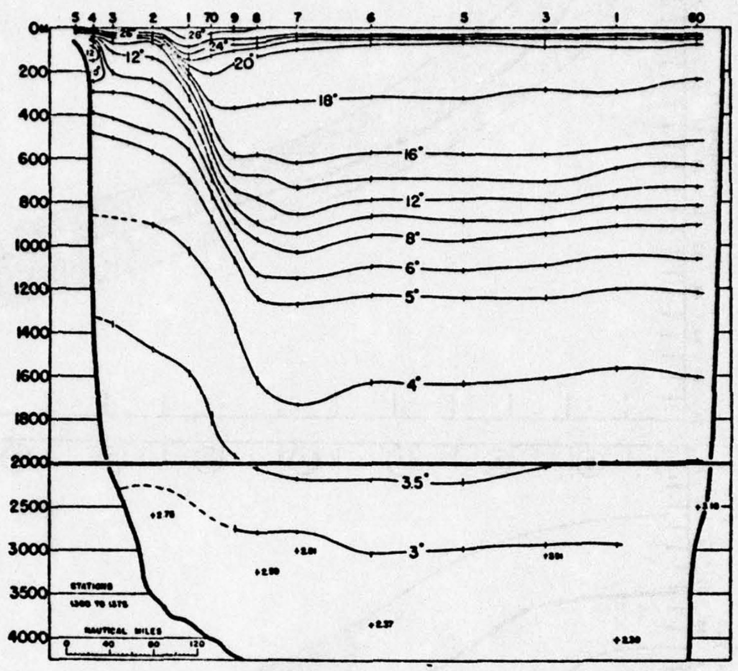


Fig. 21. Temperature section across the Gulf Stream, Chesapeake Bay to Bermuda, August 28–September 3, 1932, according to Iselin (1936, fig. 7).

Fig. 3 — Temperature section across the Gulf Stream, in February and August, showing the thermocline structure [Stommel, 1965]

upwelling areas. Some of the deeper cold currents of the ocean are simply the result of mass conservation, returing the warm water blown by the wind in the other direction.

Because of topography the currents in each of the world's ocean basins tend to form a self-contained system. The North and South Atlantic, the North and South Pacific, the Indian Ocean, and the two artic regions all have well established current patterns. The current system of the North Atlantic and the Gulf of Mexico are given in Figure 4, showing also the sea-surface temperatures and how well they relate to the currents.

In general, in each ocean basin the surface circulation is poleward to the west. In the North Atlantic and the North Pacific the gyres are clockwise, with the westward North Equatorial Current leading into the poleward Gulf and Kuroshio Currents respectively. This picture is consistent with the general atmospheric wind patterns, with the trade winds driving the westward Equatorial Current, and the mid-latitude westerlies driving the Gulf and Kuroshio eastward, and establishing the essentially wind-driven character of the water movements above the thermocline. Stommel (1965) has discussed the Gulf Stream in great detail.

A special comment must be made about the currents near the equator. The so-called North and South Equatorial Currents are actually displaced north of the equator such that the South Current is on the equator and the North Current is on 15^{O}N. In between flows the Equatorial Countercurrent in an easterly direction; this current has a high velocity core called the Cromwell Current.

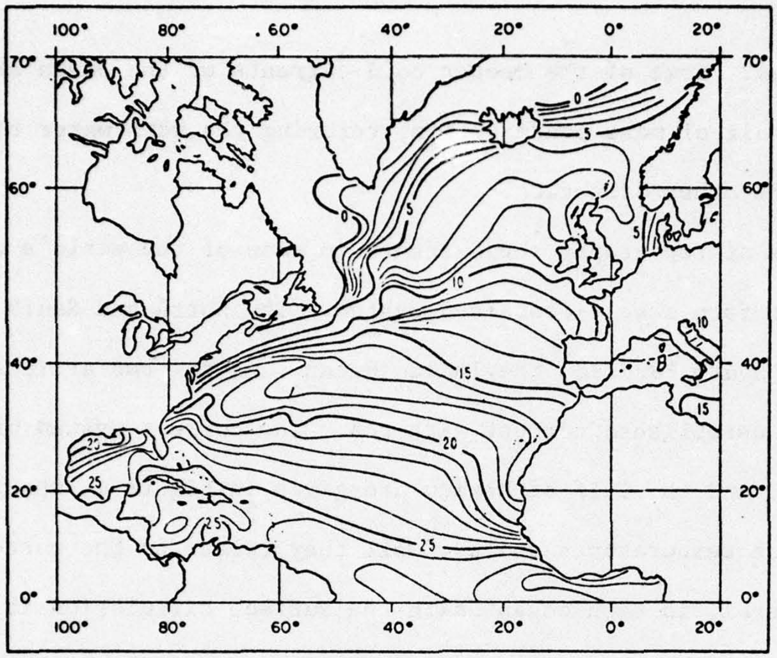


FIGURE VII-2. *The average surface temperature (°C) of the North Atlantic Ocean in April. Compare the position of the isotherms in this figure with the current paths depicted in Figure VII-3.*

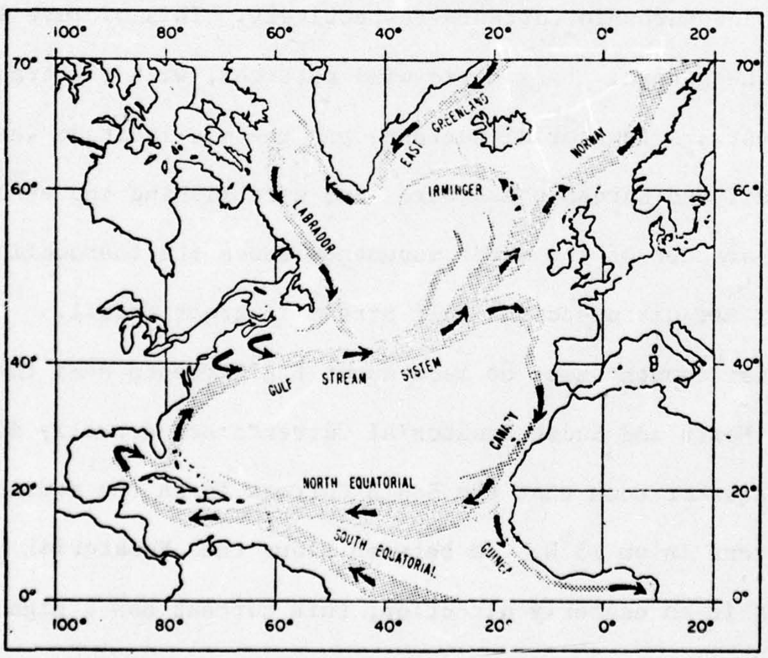


FIGURE VII-3. *Average surface currents in the North Atlantic Ocean.*

Fig. 4 — Ocean current systems of the North Atlantic are shown, along with sea-surface temperatures in April [Williams, 1962]

The deep circulation of the ocean consists of relatively strong jet-like currents that move along the continental boundaries, carrying cold arctic water towards the equator. Among these are the Labrador Current and the Brazil Current. The overall picture is rather complicated however, as Figure 5 demonstrates in showing how the polar cold water moves poleward beneath the main thermocline.

The currents that are of particular interest to the OTEC effort are the Gulf Stream, the North Equatorial Current and the undercurrents, since these will be involved in the resource assessment and environmental impact calculations for OTPP operations. The sea-surface temperatures of the western North Atlantic are shown in Figure 6 for both a typical month of February and September. The resource availability becomes clearer in Figure 3 in the vertical slices taken through the Gulf Stream for the same two months; these displays of temperature with depth and cross-stream coordinate readily shown the temperature contrast across the thermocline.

Finally, we show in Figure 7 the run of horizontal velocity in a similar slice across the Gulf Stream; as is true also of the Kuroshio, the currents in the deep are much stronger than expected from simple wind-drift or convective circulation theories.

The initial theoretical studies of ocean circulation focused on wind-driven motions of a homogeneous ocean, and these we will not review here. The more recent modeling studies fall into three general categories: a(simulations of the global ocean circulation; b) computations for single ocean basins; c) treatment of special regions such as upwellings

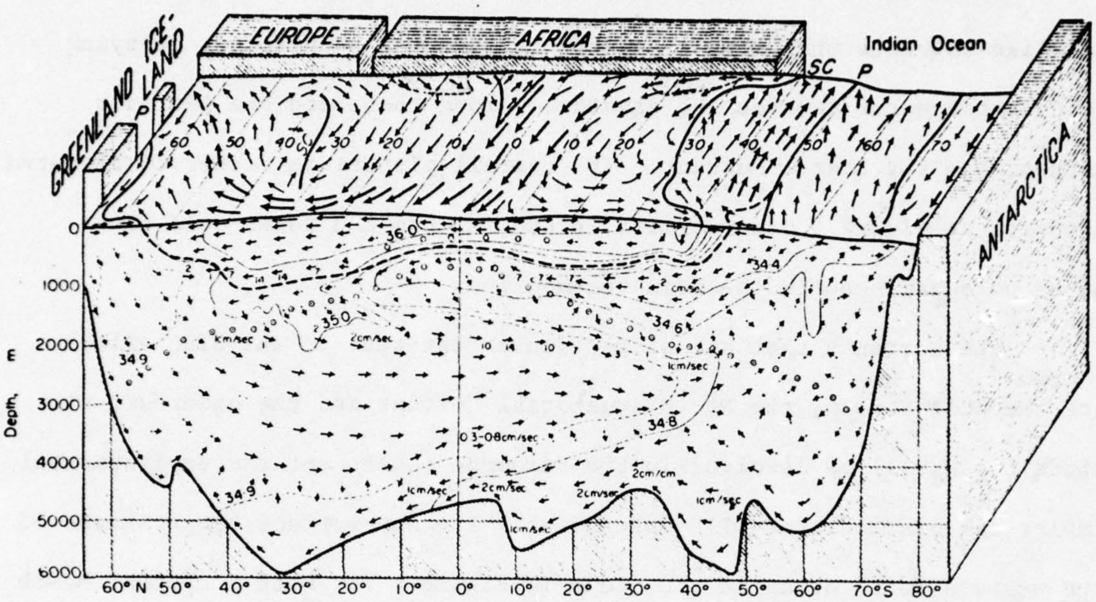


FIG. 332. Schematic block-diagram of the surface currents and of the deep sea circulation of the Atlantic Ocean (according to Wüst).

Fig. 5 — The fairly intricate deep sea circulation of cold water and the warmer surface currents of the Atlantic Ocean are shown [Defant, 1961]

and currents.

Global simulations of a baroclinic ocean have been undertaken by Crowley (1970a,b) and Bryan (1969). Although these numerical models employed rather coarse computational grids in the horizontal, they did succeed in replicating many of the large-scale observed features of the ocean circulations. Those features include the western boundary currents, like

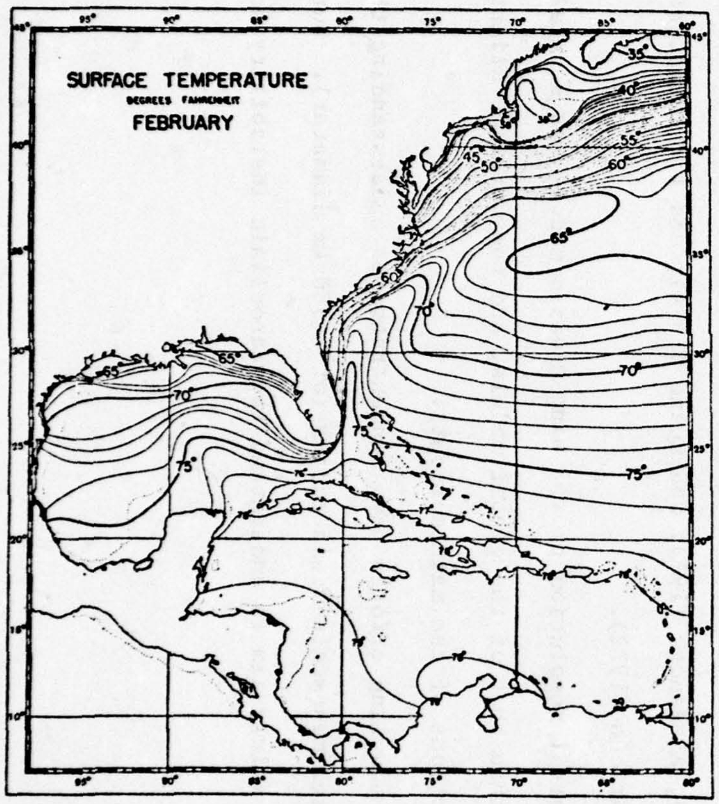


Fig. 3. Contours of surface temperature in the western North Atlantic for February, according to Fuglister (1947, pl. 2).

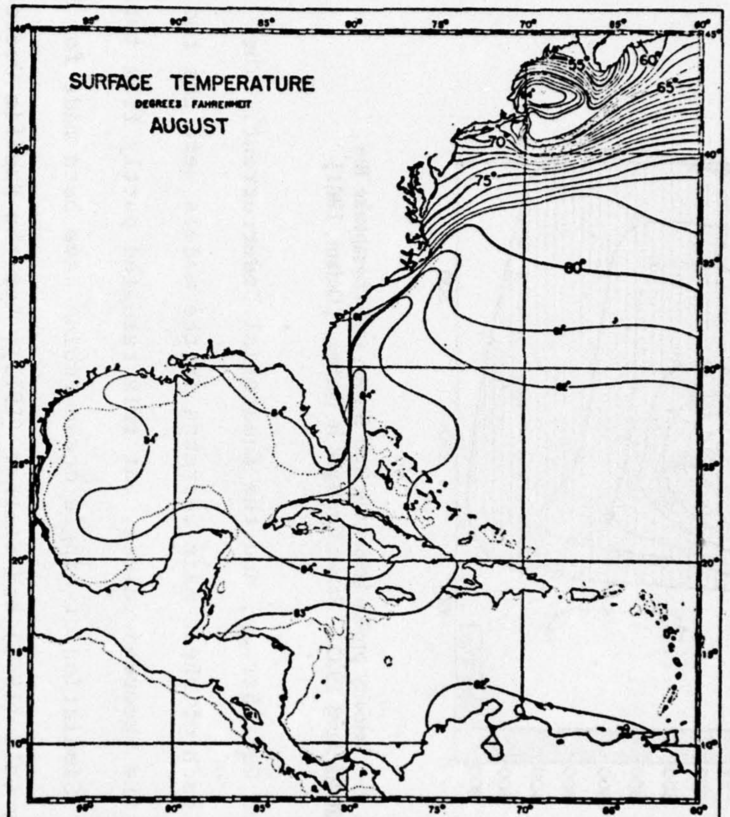


Fig. 4. Contours of surface temperature in the western North Atlantic for August, according to Fuglister (1947, pl. 8).

Fig. 6 — Contours of sea-surface temperature in the western North Atlantic are shown for February and August [Stommel, 1965]

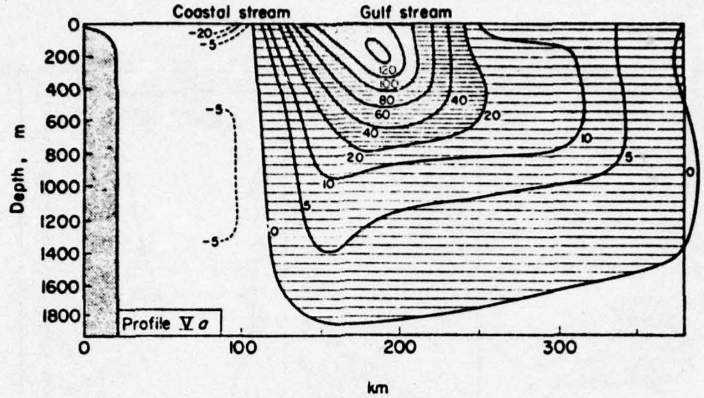


Fig. 7 — Velocity profile across the Gulf Stream (off Chesapeake Bay, 20-22 April 1932). Values displayed in cm/sec. [Defant, 1961]

the Kuroshio and Gulf Stream, and the Equatorial Undercurrent. The intensities of each of these main currents in the models were not too different from the observed values, but this resulted partly from tuning of the models. Simulation of single ocean basins have been made for the Arctic Ocean by Galt (1973) and Semtner (1973); for the Pacific Ocean by O'Brien (1969), Alexander (1973) and Huang (1974); and for the Atlantic Ocean by Friedrichs (1972).

The spatial resolution of the single basin models was several times better than that of the global models, and they provide slightly better descriptions of the main currents.

Recent modeling efforts have concentrated on understanding the newly discovered mesoscale ocean eddies (of ~ 300 km diameter). But these studies mainly aim to understand the baroclinic instability and

cascade processes which lead to the formation of those eddies from the instability of large scale currents; so far no attempt has been made to incorporate their effects in parameterised form into the large-scale (global or whole basin) models with resolutions of the order of $\gtrsim$ 300 km.

Regions of coastal upwelling have been simulated by O'Brien and Hurlburt (1972). Because of the careful incorporation of coastal and bottom topography and a high resolution mesh, the observed features of coastal upwellings was simulated very closely.

4. THERMOCLINE VARIATIONS AND AIR-SEA INTERACTION

In this chapter we shall discuss those components of the vertical oceanic temperature structure that have seasonal or diurnal variations, or that appear after the passage of storms. Because of their close relationship to these thermocline variations, we will also include a discussion of relevant air-sea interation mechanisms. Along with the observations, we will discuss the numerical models constructed to simulate and explain them.

(a) Diurnal Thermocline

Observations of the diurnal thermocline were made by Stommel et al (1969) and Ostapoff & Worthem (1974). They found that it depends on the conditions of wind and cloudiness, has a temperature change of approximately 0.1 to 1^{o}C associated with it, and has a depth of as much as 60 meters. At night convection wipes it out, so that each day a new thermocline forms on an otherwise warm mixed straight profile. Ostapoff & Worthem found a downward propagation of the heat of approximately 5 meters/hour, giving a turbulent eddy coefficient of about 100 cm^2/sec during the day. During the night, the combined effects of surface cooling and convection destroy the thermocline; where there is a density inversion, convection is a very effective mechanism for vertical transport. Figure 8 shows temperature profiles and temperature measurements at selected depths as they vary during the course of the day. The diurnal thermocline is clearly revealed in this data.

(b) Seasonal Thermocline

Figure 9 shows the seasonal variation of two representative temperature profiles in mid-latitudes. A shallow seasonal thermocline forms in June in both cases, and deepens and weakens until it disappears in February, effectively merging into the main thermocline below. The adjoining panel shows the monthly average of sea-surface temperature and downward heat flux at a particular station. Figure 2 shows the seasonal variation in the subtropics between the months of February and August. The disappearance of the strongly mixed layer (down to 300 m in February) in August is striking.

The difficult problem of simulating the seasonal thermocline was attempted by Kraus & Turner (1967) and by Turner (1969). They constructed a simple theory in which all the kinetic energy of wind stirring was assumed to change the potential energy of the system, and using a saw-tooth form of the heating function, calculated temperature and depth of the mixed layer as a function of time. They argued that in reality all effects of stirring put in near the surface propagate down without being affected by rotation or advection.

(c) Thermocline Erosion During Storms

The strong erosion of thermoclines during the passage of hurricanes has been the subject of several studies, among these the analytical studies of Geisler (1970), the numerical studies of O'Brien & Reid (1967), O'Brien (1967), and Madala & Piacsek (1974), and the ocean observations of Leipper (1967) (see Figure 12 for some of his measurements before and after hurricane

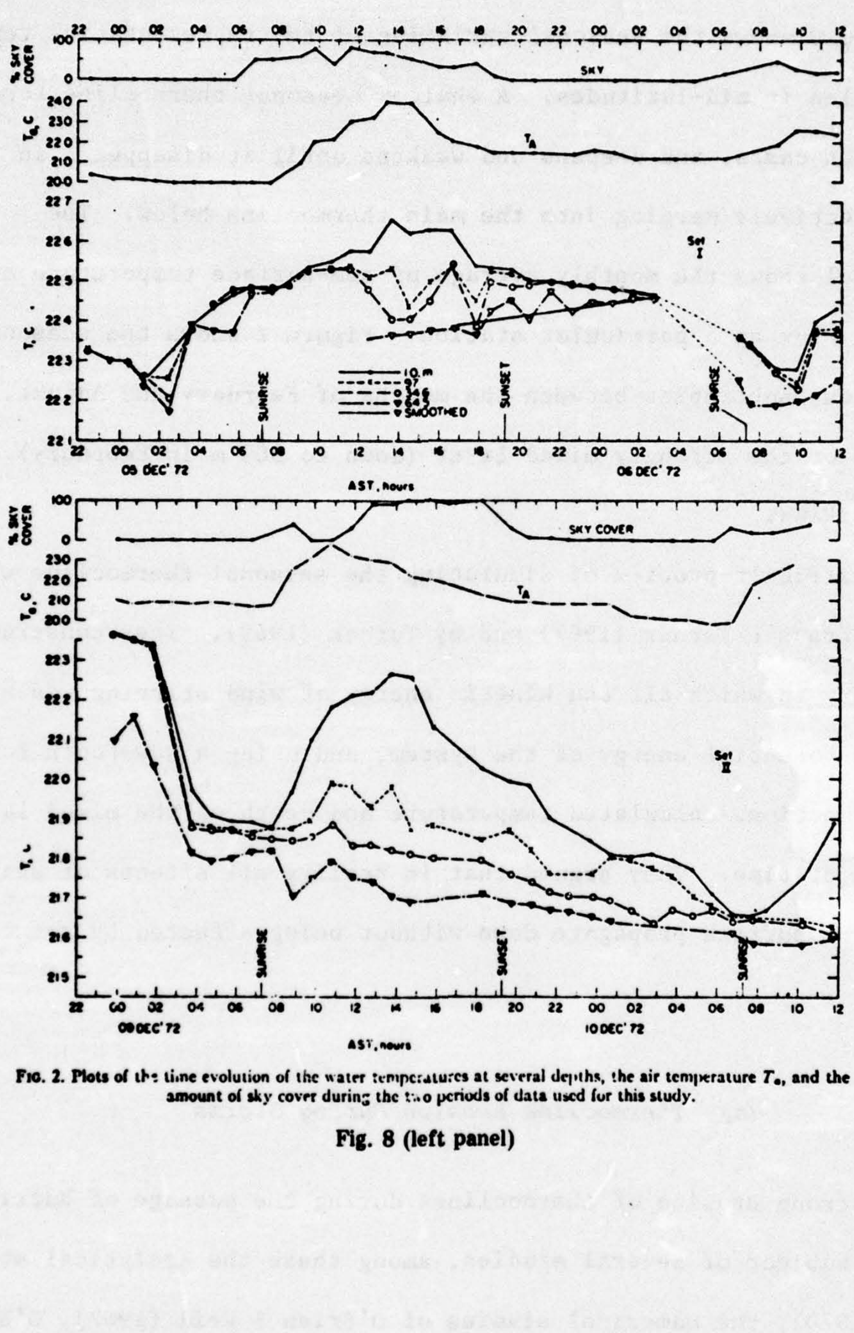


FIG. 2. Plots of the time evolution of the water temperatures at several depths, the air temperature T_a, and the amount of sky cover during the two periods of data used for this study.

Fig. 8 (left panel)

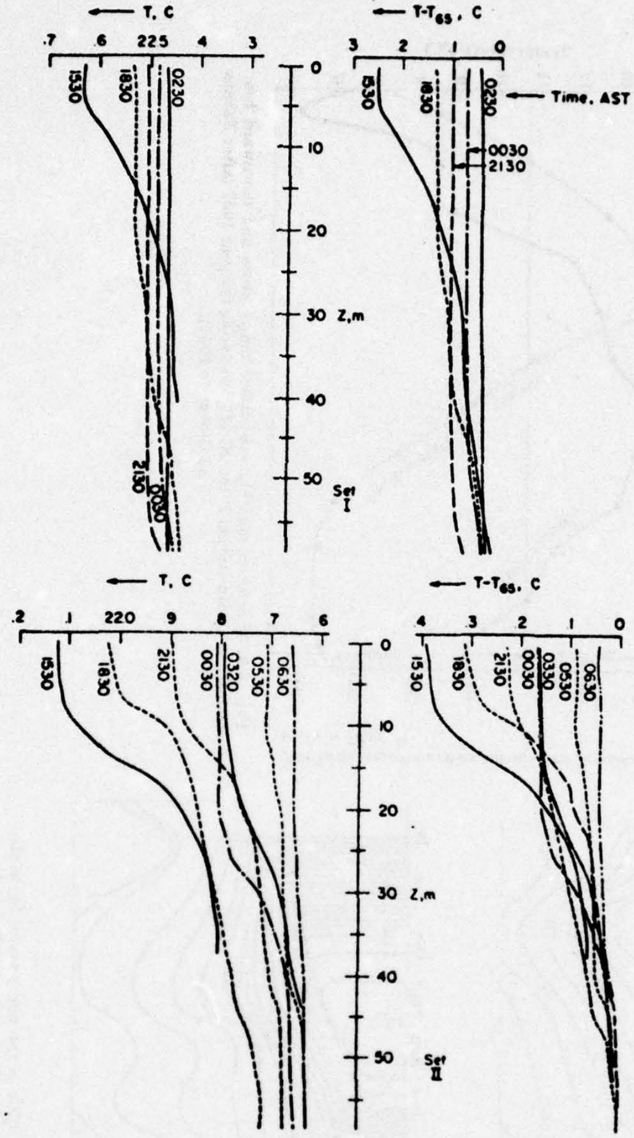


FIG. 3. Sample sounding data for the two sets of data. On the left are the actual $T(z)$ curves while those on the right are differences from the temperature at 64.5 m.

Fig. 8 — Daytime heating causes the formation of a diurnal thermocline in these time histories of water temperature with depth, shown at selected points in the left panel and as profiles in the right panels [Kaiser and Williams, 1974]

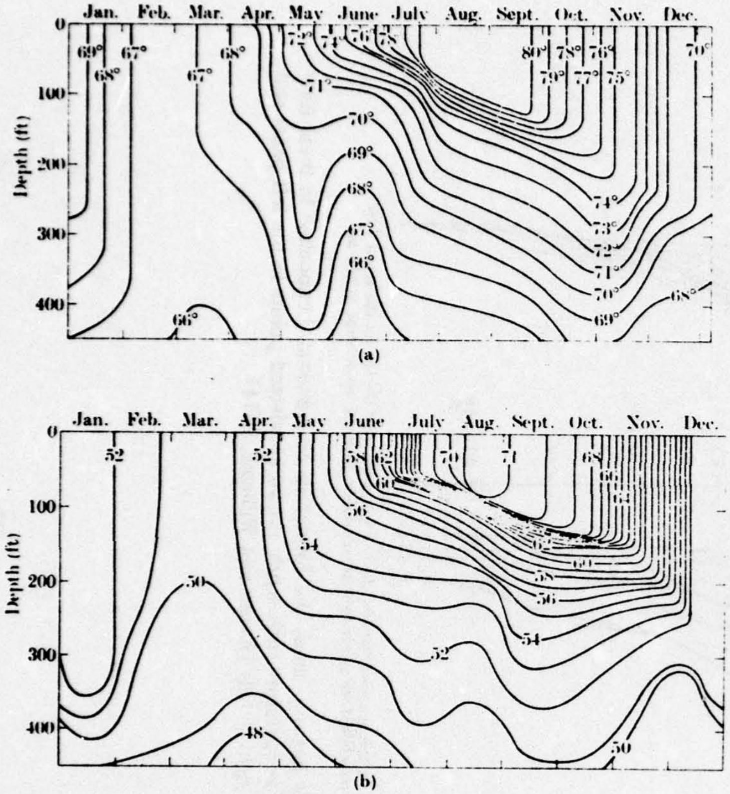


Fig. 6.5. The seasonal temperature (°F) cycle of the upper ocean (a) in the Bermuda area, (b) in the central North Pacific (from *Technical Report No. 6*, N.D.R.C., Washington, 1946).

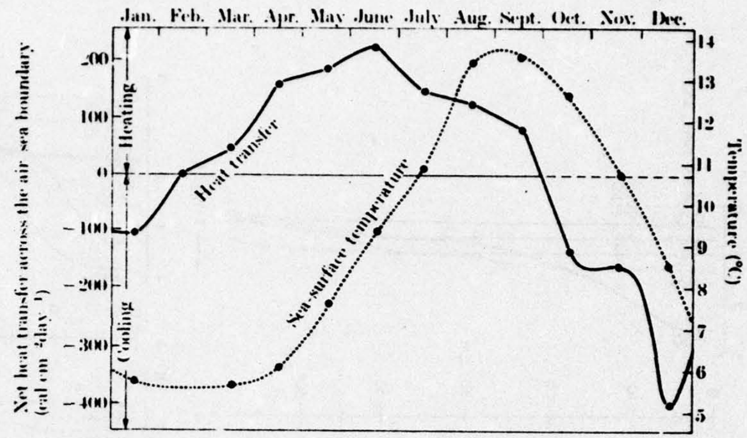


Fig. 6.6. The mean monthly sea-surface temperature and downward heat transfer at Ocean station *P* (50°N, 145°W) during the year 1957 (after Tabata and Giovando 1963).

Fig. 9 — In the left panels, the seasonal variation of temperature with depth shows the buildup of a seasonal thermocline during the summer months and its decay during the winter. The right panel displays sea-surface temperature and downward heat flux throughout a year at a given location. [Kraus, 1972]

passage). Both upwelling due to a diverging wind-driven flux in the surface layer and mixing due to turbulent entrainment are shown to contribute to the development of the new temperature structure. The recovery of this thermocline to a shape resembling pre-storm conditions is shown by the observations to take approximately two months; the models did not simulate the recovery phase. A cyclonic current system is also set up after the hurricane has passed by the large-scale perturbation of the density field; it disappears in a few weeks.

The total heat carried from the warm surface water to the colder deep water because of the hurricane is approximately 4500 cal/cm^2, spread over an area of 1.5 x 10^4 km^2. The sea-surface temperature is lowered by 5°C or more. The numerical models successfully simulated these observations, both the axisymmetric model of O'Brien & Reid and the three-dimensional model of Madala & Piacsek; the latter included the movement of the hurricane and the results showed a more realistic spatial and long-time behavior of the temperature field.

(d) One-dimensional Models of Wind Mixing

Denman & Miyake (1973) and Denman (1973) have investigated both observationally and numerically the rate and extent of the wind-induced deepening of the mixed layer during the passage of several weather disturbances in the mid-latitudes. They also observed the formation of a shallow layer of warm water under conditions of low winds and intense solar heating. Their one-dimensional numerical model successfully simulated the observed behavior during a twelve day period, despite neglecting

horizontal and vertical advection in the ocean. They concluded that for their case of spring development of the summer thermocline, these processes were not important. Pollard et al. (1973) have constructed an integral model to describe the response of the upper ocean to an imposed stress and to heating or cooling. They, too, found that on time scales of a day or less, stress dominates over heating and cooling in producing eddy diffusivity.

Mellor & Durbin (1975) constructed a model for the mixed layer and the thermocline using mean flow equations and the turbulent Reynolds stress equations. They obtained excellent agreement with observations provided by Denman & Miyake.

(e) *Air-sea Interaction*

As a whole, the oceans receive as much heat as they give up; however the heat gains and losses have a latitudinal distribution from equator to pole. More than half of the excess heat absorbed by the tropical oceans is given to the atmosphere through evaporation, and the atmosphere transports the heat (as latent heat of evaporation) toward polar regions. The large ocean currents also contribute to the poleward flow of heat; the best estimate of their share is about 30 percent. The latitude variation of the various forms of heat transport are summarized in figure 10.

Recent studies (Simpson, 1969) have indicated that in mid-latitudes the direct effects of ocean heating upon cyclone growth is small, but the indirect effect, via condensation as rainfall and corresponding latent heat release, is large. As we shall see further in section 5.b, sea-surface

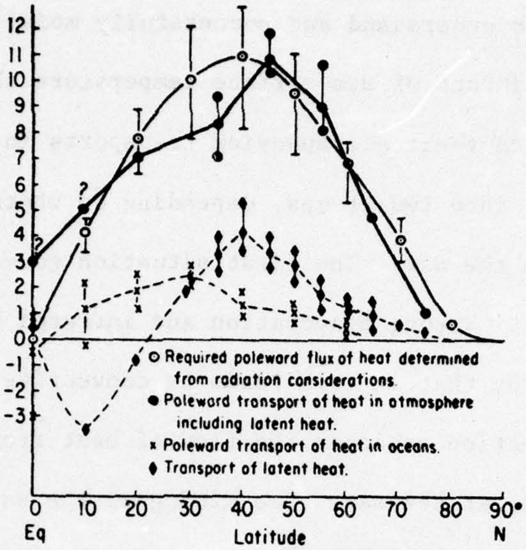


Fig. 10 — Averages and bounds of various estimated heat transports poleward [Neumann and Pierson, 1966]

temperatures associated with ocean currents, or with areas of temperature anomalies in the ocean, have a profound effect on regional climates in the respective areas of the world. The daily incidence of solar radiation, and its seasonal variation, together with the surface wind stress and wave-generated turbulence, essentially determine the location and strength of the diurnal and seasonal thermoclines.

An intimate knowledge of the air-sea exchange processes, in particular the transmission of heat and momentum and evaporation rate, is

necessary if we are to understand and successfully model thermocline behavior and climate impact of sea-surface temperature changes.

The motions and their accompanying transports in the air-sea boundary layer divide into two groups, depending on whether the water is warmer or colder than the air. The first situation generally occurs at night and in the fall. Strong evaporation and infrared back-radiation lead to surface cooling that in turn leads to convective overturning in the ocean. The convection enhances the flow of heat from the lower layers to the surface, at the same time mixing up the water and removing any shallow thermocline. The flow of heat upwards makes the overlying air boundary layer unstable by reducing its stability. So, both an increase in wind shear turbulence and in buoyancy driven convective motions will result (Delnore, 1972; Kaiser & Williams, 1974; Ostapoff & Worthem, 1974).

When the air is warmer than the water, the situation is very stable in both the water and the air, and results in accumulation of warm surface waters, aiding the diurnal and seasonal thermocline formation. Evaporation is a function of air and sea temperatures and of the relative humidity of the air, and of wind speed. Observations indicate that the maximum rate of evaporation in the oceans occurs between 10^{o} and 20^{o} latitude, this being because the cloud cover is usually greater and the wind speed smaller at the equator. Bowen's ratio, R, is defined as the ratio of sensible to evaporation heat loss from the ocean to the atmosphere. Extensive field measurements in various oceans established that in turbulent air-sea interfaces R has a value which is of order 0.1; its value is

practically independent of wind speed, and dependent only on the ocean temperature and the air temperature and humidity.

We have concentrated our attention here on heat flow processes, since these are most crucial to OTPP operation. A large body of literature exists on the generation and maintenance of surface waves, and their associated turbulence and stress; these will not be detailed here. Suffice it to say that turbulence in both the air and the water can be handled reasonably adequately by first or second-order closure methods (Deardorff, 1970; Lewellen et al, 1974a; Mellor & Durbin, 1975) or by analytical prescriptions (Munk & Anderson, 1948; Monin & Obukhov, 1954; Pandolfo, 1966; Yoshihara, 1968). An extensive discussion of the many aspects of air-sea interactions is provided by Kraus (1972).

5. WEATHER AND CLIMATE MODELING

Theoretical models concerned with the large-scale dynamics of the atmosphere can be discussed in four broad groups. Although all these models respond in some measure to the ocean surface temperature, little progress has been made in predicting atmosphere and ocean dynamics simultaneously. All these models play some role if one wishes to estimate what effects, if any, multiple OTPP operation may have on weather and climate. The first three models deal with scales smaller than global, and these regional treatments are: a) the limited area forecast models (or LAM's) for the atmosphere; b) studies correlating sea-surface temperature anomalies with regional atmosphere effects; c) hurricane simulation models. Finally in d) we briefly outline the global weather models or general circulation models (GCM's), and discuss what may be inferred from these models about climate prediction.

(a) Limited Area Forecast Models

The group operation of 100 to 1000 OTPP's calls for a region of typical diameter 1000 to 3000 km. The resulting sea-surface temperature and heat flux anomaly will affect the atmospheric motions above this region, and may produce some climate changes both in the operational region and at greater distances.

When studying atmospheric dynamics over a small portion of the globe, limited area models are embedded in a large-scale (usually global) flow. LAM's employ a very fine mesh, with grid size 10 to 50 times smaller than the grid size

associated with global circulation models. Such good spatial resolution is necessary if local weather features are to be adequately modeled. The boundary conditions for the LAM are taken to be values determined either from a GCM or from field observations, and have prescribed time variation. Usually the large-scale flow is assumed to be unaffected by the LAM flow.

Birchfield (1960), Wang & Halpern (1970), Shapiro & O'Brien (1970), and Asselin (1972) all integrated barotropic vorticity or primitive equation LAM's, and Hill (1968) a two-level baroclinic version. Considerably more elaborate multi-layer LAM's are those of Williamson & Browning (1974) at the National Center for Atmospheric Research (NCAR), and of Hovermale (1974) at the National Meteorlogical Center (NMC).

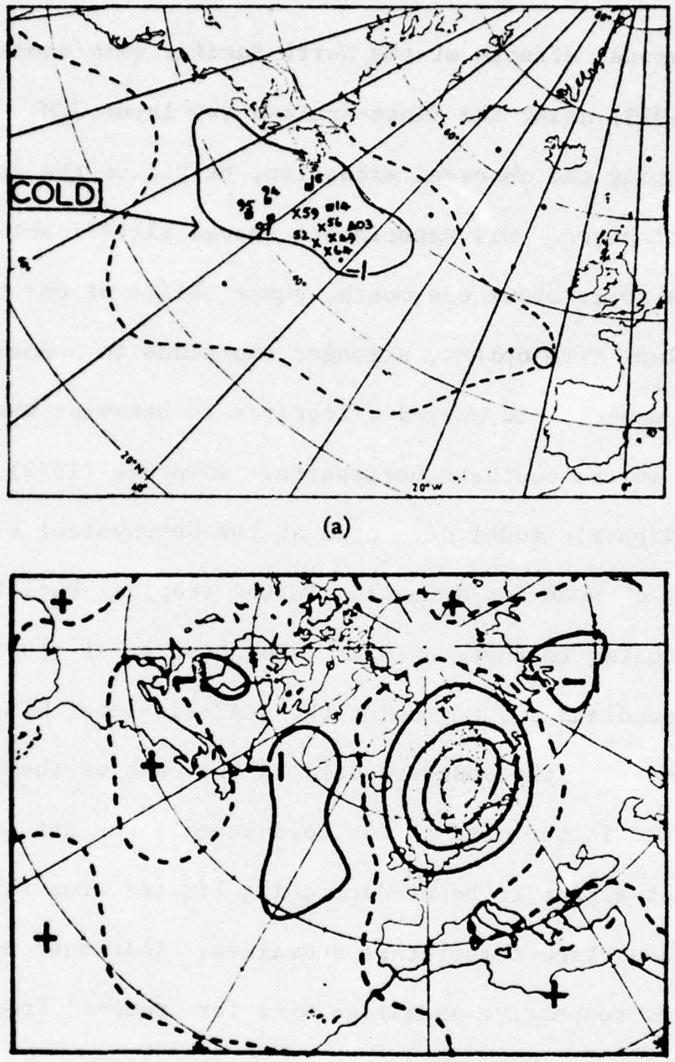
Hill, Wang, & Halpern obtained boundary conditions for the LAM's by interpolation of the data produced by a coarse GCM integration; this in time produced unwanted small-scale spatial oscillations in the solutions at the outflow edges of the LAM regions. Shapiro & O'Brien and Asselin applied similar interpolated boundary conditions at inflow points, but advected quantities out of the region with a quasi-Lagrangian scheme in order to suppress such oscillations. Oliger & Sundstrohm (1975) suggested a suitable viscous term to suppress the spatial oscillations in the LAM, and Williamson & Browning and Madala (1973) have used it successfully. In summary, these various versions of LAM's have tended to demonstrate a good potential for forecasts of a day or two.

(b) *Sea-surface Temperature Anomaly Effects*

First we shall consider the observational evidence for the permanent and temporary effects on the climate by sea-surface temperature. Next, we will examine the previous efforts to computationally simulate these anomalies phenomena.

The crucial role of the oceans in climate formation has long been recognized. The rather mild climate of northwestern Europe is attributed to the nearby passage of the Gulf Stream; the rather cool and dry climate of California in the summer is attributed to strong upwellings of cold water off the Pacific coast. More recently, scientists have also observed and tried to model associations between sea-surface temperature anomalies and changes in long-range weather patterns. Bjerknes (1966, 1969) has suggested that anomalies in the tropical Pacific influence pressure and circulation patterns in the higher latitudes. Namias (1970, 1973) has observed seasonal persistence of a large (4000 km by 2000 km) sea-surface temperature anomaly of $+6^{\circ}C$ in the North Pacific, and of its effects on the atmosphere. Ratcliffe & Murray (1970) have made similar observations on correlations between large (2000 km by 1000 km) North Atlantic sea-surface temperature anomalies of approximately $-2^{\circ}C$ south of Newfoundland and atmospheric circulation patterns of western Europe, extending over the time period 1888 to 1970, (see figure 11).

In general, the effects of such anomalies are felt downwind, carried by the global wind systems (easterly trade winds in the tropics, westerlies in the mid latitudes. Spar (1973 a, b, c) has simulated the



(a)

(b)

Figure 1. (a) Mean pattern of sea surface temperature anomaly (deg C) in September based on years with a significant negative SST anomaly area off Newfoundland. Positions of anomaly centres and last two figures of year shown :

- ■ negative anomaly > 2 deg C
- ▲ negative anomaly between 1 and 2 deg C
- × position and intensity less certain.

(b) Mean surface pressure anomaly (mb) in October for the years with a negative SST anomaly centre off Newfoundland in September as shown in Fig. 1 (a). Stippling shows area where mean anomaly is significant at 5 per cent level according to 't' test.

NOTE : In this and similar Figures zero anomalies are shown as broken lines.

Fig. 11 — Sea-surface temperature anomaly off Newfoundland is shown in upper panel, which may influence atmospheric circulation pattern over western Europe [Ratcliffe and Murray, 1970]

the monthly and seasonal effects of the North Pacific warm anomaly reported by Namias (1973) using the Mintz-Arakawa two-layer GCM. In addition to investigating the observed situation, he placed the anomaly in the Southern Hemisphere. His experiments showed significant interhemispheric effects after about one month, phase shifts of one to two weeks in major cyclone development, stronger reactions to anomalies in the winter than in the summer, and marked difference in behavior when the anomaly was placed in the Southern Hemisphere. Rowntree (1972) has used the nine-level hemispheric model developed at the Geophysical Fluid Dynamics Laboratory of NOAA for anomalies in the tropical Pacific, and obtained results similar to those of Spar. Houghton et al (1974) have simulated the Newfoundland anomaly using the NCAR six-level GCM. They found good agreement with the observed data in the case of the warm anomaly; the response in the case of the cold anomaly was not as satisfactory.

There do not appear to be studies using limited area forecast in connection with sea-surface temperature anomalies. This must be due partly to the fact that the respective anomalies were far removed from any population centers or even land areas, so there was no interest to explore their effect on neighboring regions.

The above observations suggest that anomalies of magnitude 2 to $6^{\circ}C$ and covering areas $\gtrsim 10^{6}$ km^2 may cause global weather changes. That sea-surface temperature anomalies affect neighboring areas as well is clear from the climates of western Europe and California, if we regard the Gulf Stream and the east Pacific upwelling as "permanent anomalies".

It can be expected, therefore, that even anomalies caused by large-scale OTPP operation may produce climate effects downwind (in terms of the dominant mean global circulations).

Considerable improvement in the treatment of the air-sea boundary layer processes, the parameterization of cumulus entrainment, and the release of latent heat, will be required if present weather models are to simulate anomaly effects reliably. For this reason, a large international observational effort called GATE (GARP Atmospheric Tropical Experiment) has been performed to aid the atmospheric modelers. Similarly, a large U.S. observational effort called NORPAX has commenced to study the large-scale interaction between the atmosphere and the North Pacific. Particularly, the oceanic mechanisms leading to large-scale sea-surface temperatures anomalies and their observed effects on northern hemisphere weather will be studied.

(c) Hurricane Simulation Models

There are several reasons why we should be interested in these models. Most OTPP's are expected to be located in tropical and subtropical regions, and the hurricane models are the best models suited for simulating limited area tropical atmospheric motions. The modification of hurricane formation and movement by the sea-surface temperature anomalies set up by extensive OTPP operation is an intriguing possibility which should be investigated. Even more important, the erosion and even destruction of the existing tropical thermocline by the upwelling and turbulent stresses

associated with a passing hurricane could become a serious impediment to OTPP operations (see figure 12). The hurricane models that have been employed for research or operational forecast have all been confined to atmospheric motions only, despite a strong energy and momentum exchange with the ocean.

Some of the present atmospheric models are those of Anthes (1972), Mathur (1974), Madala (1973), Madala & Piacsek (1975), and Kurihara & Tuleya (1974). The important features with which one can distinquish these models are: a) the type of mesh used; b) the number of layers in the vertical; c) the manner in which latent heat released by cumulus clouds is parameterized; d) air-sea interaction and boundary layer treatment; e) size of domain treated, including the use of an f-plane (constant Coriolis force) or a β-plane (North-South variation of Coriolis force); f) imposed large-scale flow and boundary treatment of the fine mesh.

The four models give results that differ mainly in the finer details. A general statement that can be made of all four is that they successfully simulated the magnitude of the central pressure minimum, the rate of intensification of the storm, the spiral cloud bands and associated confluence and diffluence lines in the stream function, the organized bands of clouds near the eye, the downward motion in the eye, and the cyclonic outflow in the upper troposhere. Mathur's and Madala's models are on a β-plane, allowing the hurricane to move, and all except Kurihara have three layers in the vertical, while he used eleven. All have used explicit time differencing techniques, except Madala, who used a semi-

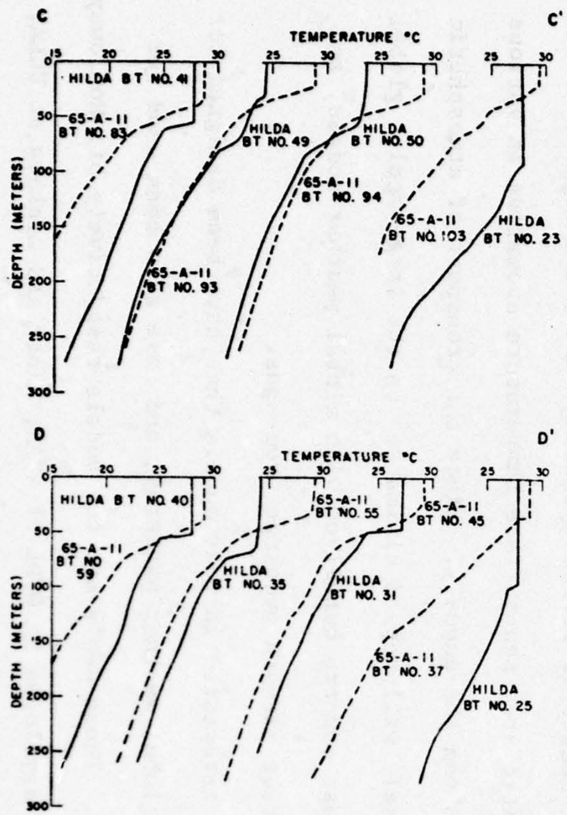


FIG. 13. Comparisons of temperature-depth structures at identical locations for the undisturbed Gulf, 1965, and the GUS III cruise after Hilda. Figs. 13 a–c are along sections B, C and D, respectively. Locations may be identified on Fig. 2 and Fig. 5.

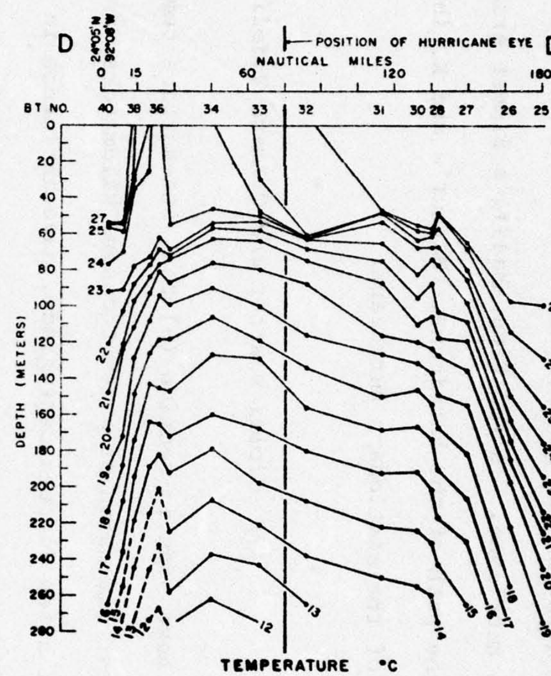


Fig. 12 — Measurements of ocean temperature profiles before and after the passage of hurricane Hilda are shown in the left panels, with distinct erosion effects on the thermocline structure. The right panel shows the cooling effects of the upwelling flow established along the path of the hurricane. [Leipper, 1967]

implicit scheme to overcome fast gravity waves. Also, Mathur used two, and Madala three, nested grids, the finest mesh located over the central part of the hurricane. In addition, Madala's finest grid was movable, following the path of the hurricane, Mathur's and Kurihara's were fixed on the eye of the stationary hurricane.

(d) Global Weather and Climate Modeling

We have seen in section (b) that sea-surface temperature anomalies with a modest dimension of a few thousand kilometers, and temperature deviations of a few degrees Centigrade, have influence in changing long-term weather patterns in regions of the globe removed from the anomaly.

For a large number of OTPP's operating, one could begin to examine the effects of limited area sea-surface temperature anomalies in various locations downwind from the anomaly. Since the transport of atmospheric effects of the anomaly will depend ultimately on the large-scale global wind systems, we must concern ourselves with global weather models, and their ability to treat air-sea exchange processes.

We will be interested in four models that have been designed for the prediction of global weather patterns, and have also been used for climate simulation. These GCM's are the models respectively of: Holloway and Manabe (1971), developed at GFDL of NOAA; Mintz and Arakawa at UCLA, documented by Arakawa et al (1969) and Gates et al (1971); Somerville et al. (1974) at GISS (NASA Goddard Institute for Space Studies, New York); and Kasahara and Washington (1971) at NCAR.

In many ways these GCM's are quite arbitrary in how certain physical processes are parameterized, and the recipes vary with the model. Still, these models provide the best apparatus for performing controlled experiments on the highly nonlinear dynamics of the atmosphere.

For the sake of brevity, the four GCM's could be partly characterized with how each treats items a) to f) listed on page 46. One other notable characteristic in distinguishing between these models is the choice of independent variable for the vertical coordinate. The height z, the pressure p, log p, or the ratio $\sigma = p/p_s$ (where p_s is the variable surface pressure) have all been used by various modelers of atmosphere phenomena.

All except the NCAR model use the σ coordinate, with NCAR using the height z. The GISS (9 vertical layers) and the UCLA (2 layers) models use Arakawa's parameterization of cumulus clouds, whereas NCAR (6 layers) and GFDL (9 layers) use " moist convective adjustment". In both the GISS and UCLA models there is no horizontal diffusion, whereas NCAR and GFDL use the nonlinear viscosity deduced by Smagorinsky (1963). The vertical diffusion is mixing-length dependent in the GFDL model, while in the GISS and NCAR models it is given by an expression (Deardorff, 1967) containing Richardson number and the potential temperature gradient.

The Kurihara (GFDL) model uses the box method for generating the global mesh (successive latitude belts containing fewer boxes) such that all boxes on the sphere, except at the poles, have the same size. This method is a much more efficient way of covering the globe than the latitude-longitude intersections, which put too many points at the poles. All four

models use leap-frog time differencing for the advection and pressure terms, and a lagged time step for the friction term (Williams, 1969). The time step allowed by these methods is very small, usually because of the fast gravity waves present in the system; conversion to the semi-implicit scheme of Robert (1971) would be highly desirable.

Because of the limitations of only two layers in the vertical, the UCLA model does not perform as well on the baroclinic aspects of the problem as the others. In overview, probably the GISS and GFDL models with nine layers yield the best simulations of the atmospheric dynamics.

All GCM's are accompanied by a "predictability limit" due to imperfect initial conditions, finite spatial resolution, accumulated time truncation and perhaps round-off errors. A small change in the system of equations or in initial conditions will produce changes in the atmospheric variables which increase by an order of magnitude every five days or so; thus one cannot readily distinguish between effects of small errors or small changes in the environmental parameters (e.g. solar radiation, polar ice cover, etc). Nevertheless, since in climate studies one is only interested in certain averaged states (or statistical behavior) of the atmosphere, several workers carried out GCM experiments to study the seasonal variations of the atmosphere or the climate determined by different sets of the environmental parameters. The results indicate that large-scale changes of the environmental conditions will indeed lead to a computable climate change. A reproduction of the climate for one month of the year was performed by Manabe et al. (1970), Washington & Kasahara (1970),

Gates (1972), and Somerville et al. (1974). All chose the month of January and all succeeded in simulating some of the essential features of the zonally averaged mean flow field and the heat and water budgets (see figure 13). In all these experiments the solar radiation and the sea-surface temperature were held constant at values corresponding to January.

The seasonal variation of the atmosphere has been simulated by Manabe et al (1974) who used an eleven-layer GCM model to study the response of the atmosphere to insolation (incident solar radiation) and sea-surface temperature over a three year period. The model accurately simulated the seasonal variation of the location of the tropical rain belt. Over the oceans this belt had a tendency to form away from the equator, which the authors attributed to the equatorial belt of low sea-surface temperatures.

The seasonal variation of the tropical atmosphere due to seasonal changes in the sea-surface temperatures has also been investigated by Pike (1972) using a joint atmosphere-ocean model. He used a simple zonally averaged two-dimensional model but included two layers of the upper ocean without continents. He obtained qualitative agreement on the migration of a single mode of the ITCZ (inter-tropical convergence zone) and the lag of the maximum subequatorial sea-surface temperature behind the overhead sun.

A combined global ocean-atmosphere simulation was carried out by Manabe (1969) to identify various influences of the circulation of the oceans on the general circulation and the hydrologic cycle of the atmosphere. The integration was performed for one atmospheric model year and a hundred oceanic years, the two time scales overlapping to make the computational

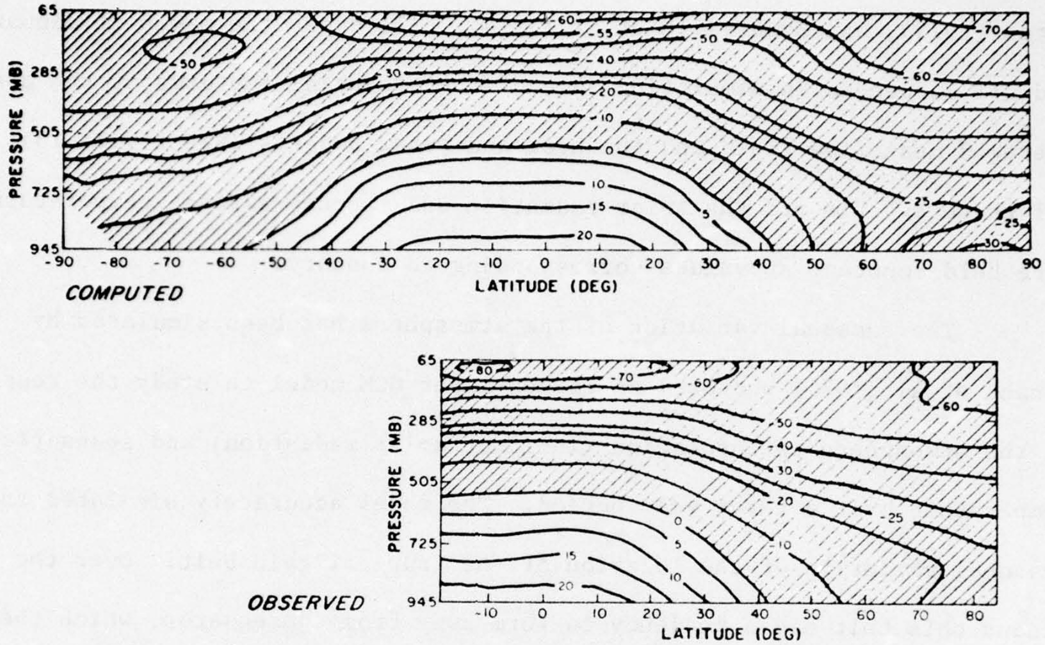


FIG. 17. Computed and observed January zonal mean fields of temperature (°C). Observed field is based on data from Oort and Rasmusson (1971). Negative regions are shaded.

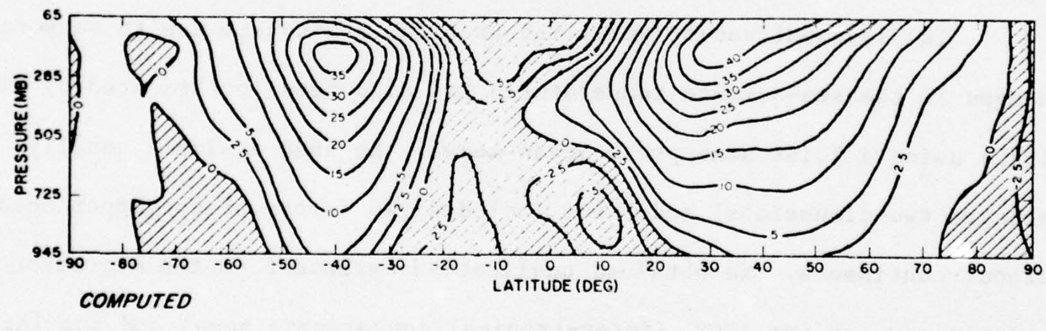


FIG. 14. Computed and observed January zonal mean fields of zonal wind (m sec^{-1}). Observed field is based on data from Oort and Rasmusson (1971). Negative (easterly) regions are shaded.

Fig. 13 — Results of GISS general circulation model (GCM) calculations of a January climate, compared to observations [Somerville et al., 1974]

time reasonable. Even though the joint model consumed 500 hours of CDC 6600 machine time, without the deeper layers of the ocean coming into equilibrium, some of his findings were: a) the reduction of the poleward transport of latent and heat energy by the atmosphere due to ocean currents; b) an increase in the temperature contrast between oceans and continents in middle and high latitudes, enhancing the development of cyclones off the East Coast; c) at the equator the upwelling of cold water tends to suppress tropical rainfall over the ocean but increase it over the continents; d) the middle latitude rain belt shifts poleward due to the ocean current.

Next, we must mention an interesting climatic change experiment by Washington (1972), who investigated the possible climatic changes caused by the release of all thermal pollution associated with the energy use of all mankind. Assuming a population of 20 billion and a personal use of 15 kw with a realistic population distribution, he found that the addition or subtraction of 3×10^{14} kw to the atmosphere produced the same changes in the final state after 40 days of iteration that the addition of a small initial error has made. It appeared therefore that the effect of the thermal pollution was smaller than the natural fluctuations of the model. The result of Washington does not preclude a possible climate change by thermal pollution of the ocean, or at least of its deep layers, because the previous experiments of Pike (1972), Manabe et al (1974), and Spar (1973 a, b, c) have all shown regional climate changes due to local sea-surface temperature changes. Somerville (1976b) has demonstrated global

changes in a study of GCM sensitivity to sea-surface temperature.

The GCM's have also been used to study effects on climate when much larger changes were imposed through the boundary conditions. Williams, Barry & Washington (1974) have used the NCAR GCM to simulate typical winter and summer weather conditions with a snow and ice cover appropriate to a glacial maximum. Other studies consider the effects of modifying the solar flux constant, as in work of Somerville et al. (1976a) using the GISS GCM code. Although such climatic research is not directly applicable to OTPP problems, it does serve to illustrate some of the more extreme climate modification studies based on GCM's.

6. MARINE ECOSYSTEMS

The ecological balance processes in the deep ocean are complicated and have a large literature. Studies on the modeling of these processes have been given by Platt & Denman (1975) and Raymont (1966). Briefly, phytoplankton growth depends on light intensity and the presence of sufficient nutrient (nitrate, ammonia and phosphate). Zooplankton consume phytoplankton, and fish consume both. Dead organisms tend to sink, and then rot at greater depths, so that nutrient is continually carried away from the sunlit area by falling detritus. Thus in most of the ocean, marine life is nutrient-limited. (Verhoff, 1971; Thomas & Dodson, 1968; Thomas, 1970; MacIsaac & Dugdale, 1969; Corner & Davies, 1971).

To obtain empirical equations describing these different processes, together with horizontal and vertical advection and vertical turbulent transport of the different organisms, is relatively easy. To obtain equations giving good agreement with observations over large ocean regions is more difficult, and it is fair to say that only moderate progress has been made so far (Steele, 1959; Riley, Stommel & Bumpus, 1949).

The importance of upwellings to the marine ecology has long been recognised (Bogdanov, Sokolov & Khromov, 1968; Cushing, 1969; Dugdale, 1967; Glooschenco, Curl & Small, 1972). O'Brien & Wroblewski (1973), Wroblewski, O'Brien & Platt (1974), and Wroblewski & O'Brien (1975) have modeled the dynamics as well as the ecology, in order to explain observed features of the plankton distribution.

In regard to OTPP operation, the limiting nutrient is a passive scalar in the near-field, since the time-scale is too short for significant changes in the marine life. But a detailed ecosystem model, possibly of a horizontal average type, is required to estimate the possible economic benefits produced by the huge upward nutrient flux associated with OTPP operation.

ACKNOWLEDGMENTS

This report has provided background material and brief assessments of the several areas of geophysical fluid dynamics that have direct bearing on the research program *"Theoretical fluid dynamical studies of resource availability and environmental impact of ocean thermal power plants"* , supported by the Ocean Thermal Energy Conversion Program, Division of Solar Energy, Energy Research and Development Administration, under ERDA contract E (49-26) 1005 to the Naval Research Laboratory, with a subcontract to Science Applications, Inc.

The primary illustrations in this working document draw upon the published literature in geophysical fluid dynamics. In particular, we are indebted for the reproduction of the following illustrations from the cited sources: *Defant (1961):* figure 1, *p 120/fig 54;* figure 5, *p 697/fig 332;* figure 7, *p 612/fig 284.* *Kaiser & Williams (1974):* figure 8, *p 140/fig 2, p 141/fig 3.* *Kraus (1972):* figure 9, *p 191/fig 6.5, p 192/fig 6.6.* *Leipper (1967):* figure 12, *p 191/fig 12, p 192/fig 13.* *Neumann & Pierson (1966):* figure 10, *p 248/fig 9.15.* *Oceanography Atlas (1967):* figure 2, *p 174/fig II-96.* *Ratcliffe & Murray (1970):* figure 11, *p 229/fig 1.* *Somerville et al. (1974):* figure 13, *p 97/fig 14, p 99/fig 17.* *Stommel (1965):* figure 3, *p 45/fig 19, p 47/fig 21;* figure 6, *p 24/fig 3, p 25/fig 4.* *Williams (1962):* figure 4, *p 92/fig VII-2, p 93/fig VII-3.*

REFERENCES

AHN, C.S., SMITH, P.F. (1972) "The First Report of a Study to Forecast Nuclear Power Plant Effects on Coastal Zones," Report UC-12, EG&G Environmental Services, Waltham Mass.

ALEXANDER, R.C. (1973) "Ocean Circulation and Temperature Prediction Model: In the Pacific," Rand Corp. Report R-1296-ARPA.

ANTHES, R.A. (1972) "Development of Asymmetrics in a Three-Dimensional Numerical Model of the Tropical Cyclone," Mon Weather Rev. 100, 461.

ARAKAWA, A. KATAYAMA, A. & MINTZ, Y. (1969) "Numerical Simulation of the General Circulation of the Atmosphere," Proc. WMO/IUGG Symp. Numerical Weather Prediction, Tokyo, Japan Meteor Agency IV, 7, 812.

ASSELIN, R. (1972) "Integration of a Semi-Implicit Model with Time-Dependent Boundary Conditions," Atmosphere 10, 44.

BAUMGARTNER, D.J., TRENT, D.S. (1970) "Ocean Outfall Design, Part 1, Literature Review and Theoretical Development," U.S. Dept. of Interior Report, Federal Water Quality Administration, Pacific Northwest Water Laboratory, Corvallis, Oregon.

BELL, T.M. (1973) "Internal Wave Generation by Submerged Bodies: Mean flow Effects," NRL Memorandum Report No. 2553.

BELL, T., DUGAN, J.P. (1973) "Mixed Region Collapse in a Stratified Fluid," NRL Memorandum Report No. 2564.

BIRCHFIELD, G.E. (1960) "Numerical Prediction of Hurricane Movement with the Use of a Fine Grid," J. Meteor. 17, 406.

BIRINGEN, S. (1975) "The Prediction of an Axisymmetric Turbulent Jet by a Three-Equation Model of Turbulence," Institut von Karman de dynamique des fluides, Note Technique No. 114, Rhode - Saint - Genese, Belgium.

BJERKNES, J.A. (1966) "A Possible Response of the Atmospheric Hadley Circulation to Equatorial Anomalies of Ocean Temperature," Tellus 18, 920.

BJERKNES, J.A. (1969) "Atmospheric Teleconnections from the Equatorial Pacific," Mon Weather Rev. 97, 153.

BOGDANOV, D.W., SOKOLOV, V.A., KHROMOV, N.S. (1968) "Regions of High Biological and Commercial Productivity in the Gulf of Mexico and Caribbean Sea", Oceanology 8 (3), 371.

BRYAN, K. (1969) "A Numerical Method for the Study of the Circulation of the World's Oceans," J. Comp. Phys. 4, 347.

CHAN, R.K.-C., HIRT, C.W., YOUNG, J.A. (1972) "Computer Simulations of Turbulent Wakes and Related Surface Effects," SAI Report 72-580-LJ, Science Applications, Inc., La Jolla, California.

CORNER, E.D.S., DAVIES, A.G. (1971) "Plankton as a Factor in the Nitrogen and Phosphorus Cycles in the Sea" in F.S. Russell and M. Yonge (eds.), Adv. Mar. Biol. 9, 101.

CROWLEY, W.P. (1970a) "A Numerical Model for Viscous Free-Surface Barotropic Wind-Driven Ocean Circulations", J. Comp. Phys. 5, 139.

CROWLEY, W.P. (1970b) "A Numerical Model for Viscous Non-Divergent Barotropic Wind-Driven Ocean Circulations", J. Comp. Phys. 6, 183.

CUSHING, D.H. (1969) "Models of the Productive Cycle in the Sea", Morning Review Lectures at the Second International Oceanographic Congress, p. 103, Paris, UNESCO.

DEARDORFF, J.W., (1967) "Empirical Dependence of the Eddy Coefficient for Heat Upon Stability Above the Lowest 50MS," J. Appl. Meteor. 6, 631.

DEARDORFF, J.W. (1970) "A Three-Dimensional Numerical Investigation of the Idealized Planetary Boundary Layer," Geophys. Fluid Dynam., 1, 377.

DEARDORFF, J.W. (1974) "Three-Dimensional Numerical Study of the Height and Mean Structure of a Heated Planetary Boundary Layer", Boundary Layer Meteorology 7, 81.

DEFANT, A. (1961), "Physical Oceanography, Vol. I," Pergamon Press.

DELNORE, V.E. (1972) "Diurnal Variations of Temperature and Energy Budget for the Oceanic Mixed Layer During BOMEX," J. Phys. Oceanogr., 2, 39.

DENMAN, K.L., MIYAKE, M. (1973) "Upper Layer Modification at Ocean Station Papa," J. Phys. Oceanogr., 3, 185.

DENMAN, K.L., (1973) "A time-dependent Model of the Upper Ocean," J. Phys. Oceanogr., 3, 173.

DUGAN, J., WARN-VARNAS, A., PIACSEK, S.A., (1973) "Numerical Model for Mixed Region Collapse in a Stratified Fluid," NRL Memorandum Report No. 2597.

DUGDALE, R.C. (1967) "Nutrient Limitations in the Sea: Dynamics Identification, and Significance," Limnol. Oceanog. 12, 685.

DUGGER, G.L. (1975) "Proceedings, Third Workshop on Ocean Thermal Energy Conversion," Report SR 75-2, Applied Physics Lab. Laurel, Md.

DUNN, W.E., POLICASTRO, A.J., PADDOCK, R.A. (1975) "Surface Thermal Plumes: Evaluation of Mathematical Models for the Near and Complete Field," Center for Environmental Studies Report, Argonne National Lab., Ill.

FAN, L-N, (1967) "Turbulent Buoyant Jets into Stratified or Flowing Ambient Fluids," W.M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Report No. KH-R-15.

FRIEDRICHS, H.J. (1972) "Preliminary Results from a Numerical Multi-layer Model for the Circulation of the North Atlantic," Deutsch Hydrogr. Zeits, 23, 145.

GALT, J.A. (1973) "A Numerical Investigation of Arctic Ocean Dynamics," J. Phys. Oceanogr., 3, 379.

GATES, W.L. (1972) "The January Global Climate Simulated by the Two-Level Mintz -Arakawa Model: A Comparison with Observation," Rept. R-1005-ARPA, Rand Corporation.

GATES, W.L., BATTEN, E.S., KAIRE, A.B., NELSON, A.B. (1971) "A documentation of the Mintz-Arakawa Two-Level Atmospheric General Circulation Model," Rept. R-877-ARPA, Rand Corp.

GEISLER, J.E. (1970) "Linear Theory of the Response of a Two Layer Ocean to Moving Hurricanes," Geophys Fluid Dynam. 1, 249.

GLOOSCHENCO, W.A., CURL, H., SMALL, L.F. (1972) "Seasonal Primary Production in a Region of Upwelling," J. Fish. Res. Bd. Canada, 29, 1253.

GRAN, R.L. (1973) "An Experiment on the Wake of a Slender Propellor-Driven Body," Report TRW-20086-6006-RU-00, TRW.

HERONEMUS, W.E., et al. (1973) Univ. of Mass. (Amherst) Progress Report NSF/RANN/SE/GI-34979/PR/73/2-1973, July 31 - "Research applied to Ocean Sited Power Plants".

HERONEMUS, W.E., et al. (1974a) Univ. of Mass. (Amherst) Progress Report NSF/RANN/SE/ GI-34979/PR/73/3-1974, Jan. 25 - "Research applied to Ocean Sited Power Plants".

HERONEMUS, W.E., et al. (1974b) Univ. of Mass. (Amherst) Progress Report NSF/RANN/SE/GS-34979/PR/74/1 - 1974, April 30, "Research applied to Ocean Sited Power Plants".

HERRING, J.R., KRAICHNAN, R.H. (1971) "Statistical Models of Turbulence", ed. M. Rosenblatt, C. Van Atta, Berlin, Springer, 148.

HILL, G.E., (1968) "Grid Telescoping in Numerical Weather Prediction," Jour. App. Meteor. 7, 29.

HOLLOWAY, J.L., JR., MANABE, S. (1971) " Simulation of Climate by a Global General Circulation Model: I. Hydrologic Cycle and Heat Balance," Mon. Weather Rev. 99, 335.

HOUGHTON, D.D., KUTZBACH, J.E., MCCLINTOCK, M, SUCHMAN, D. (1974) "Response of a General Circulation Model to a Sea Temperature Perturbation," J. Atmos. Sci. 31, 857.

HOVERMALE, J.B. (1974) "An Operationally Oriented Grid Nesting Technique," Trans. A.G.U. 55, 260.

HUANG, J.C.K. (1974) "Seasonal Variability of Transports in the North Pacific Ocean from Numerical Simulation Study," Trans. A.G.U. 55, 305.

JIRKA, G.H., ABRAHAM, G., HARLEMAN, D.R.F. (1975) "An Assessment of Techniques for Hydrothermal Prediction," Ralph Parsons Lab. Report 203, MIT, Cambridge, Mass.

KAISER, J.A.C., WILLIAMS, K.G. (1974) "Measurements of the Vertical Heat Flux in the Upper Ocean Layer," J. Phys. Oceanogr. 4, 137.

KASAHARA, A., WASHINGTON, W. (1971) "General Circulation Experiments with a Six-Layer NCAR Model, Including Orography, Cloudiness and Surface Temperature Calculations," J. Atmos. Sci. 28, 657.

KO, D.R.S. (1973) "A Phenomenological Model for the Momentumless Turbulent Wake in a Stratified Medium", TRW Report 20086-6007-RU-00.

KOH, R.C.Y., FAN,L.-N. (1970) "Mathematical Models for the prediction of Temperature Distributions Resulting from the Discharge of Heated Water into Large Bodies of Water," National Environmental Protection Agency Report, Water Pollution Control Research Series 16130DW010/70.

KRAICHNAN, R.H. (1959) "The Structure of Isotropic Turbulence at Very High Reynolds Numbers", J. Fluid Mech. 5, 497.

KRAICHNAN, R.H. (1971) "An Almost-Markovian Galilean-Invariant Turbulence Model", J. Fluid Mech. 47, 513.

KRAICHNAN, R.H. (1973) "Test Field Model for Inhomogeneous Turbulence", J. Fluid Mech. 56, 287.

KRAUS, E.B., TURNER, J.S. (1967) "A One-Dimensional Model of the Seasonal Thermocline. II The General Theory and its Consequences," Tellus 19, 98.

KRAUS, E.B. (1972) "Atmosphere Ocean Interaction," Oxford University Press.

KURIHARA, Y., TULEYA, R.E. (1974) "Structure of a Tropical Cyclone Developed in a Three-Dimensional Numerical Simulation Model," J. Atmos. Sci. 31, 893.

LAUNDER, B.E. (1975) "On the Effects of a Gravitational Field on the Turbulent Transport of Heat and Momentum," J. Fluid Mech. 67, 569.

LAVI, A. (editor) (1973) "Proceedings, Solar Sea Power Plant Conference and Workshop," (Pittsburgh, Pennsylvania, 1973 June 27 and 28) NSF/RANN/SE/GI-39115-1973.

LEWELLEN, W.S., TESKE, M., DONALDSON, duP. (1973a) "Application of Turbulence Model Equations to Axisymmetric Wakes," ARAP Report 191, Aeronautical Research Assoc. of Princeton, N.J.

LEWELLEN, W.S., TESKE, M. (1973b) "Prediction of the Monin-Obukov Similarity Functions from an Invariant Model of Turbulence, J. Atmos. Sci. 30, 1340.

LEWELLEN, W.S., TESKE, M., CONTILIANO, R., HILST, G.R., DONALDSON, C. duP. (1974a) "Invariant Modeling of Turbulence and Diffusion in the Planetary Boundary Layer", ARAP Report 225, Aeronautical Research Associates of Princeton, N.J.

LEWELLEN, W.S., TESKE, M., DONALDSON, C. duP. (1974b) "Turbulent Wakes in a Stratified Fluid", ARAP Report 226, Aeronautical Research Associates of Princeton, N.J.

LEIPPER, D.F. (1967) "Observed Ocean Conditions in Hurricane Hilda, 1964," J. Atmos. Sci. 24, 182.

MacISAAC, J.J., DUGDALE, R.C. (1969) "The Kinetics of Nitrate and Ammonia Uptake by Natural Populations of Marine Phytoplankton", Deep-Sea Res. 16, 415.

MADALA, R.V. (1973) "A Three-Dimensional Numerical Model of the Life Cycle of a Hurricane," Ph.D. Thesis, Florida State Univ.

MADALA, R.V., PIACSEK, S.A. (1974) "On the Influence of Stationary and Moving Hurricanes on the Upper 2 km layer of the Ocean," Trans. A.G.U. 35, 305.

MANABE, S. (1969), "Climate and the Ocean Circulation, II. The Atmospheric Circulation and the Effect of Heat Transfer by Ocean Currents," Mon Weather Rev., 97, 775.

MANABE, S., STONE, H.M., (1970) "Tropical Circulation in a Time-Integration of a Global Model of the Atmosphere," J. Atmos. Sci. 27, 580.

MANABE, S., HAHN, D.G., HOLLOWAY, J.L. (1974) "The Seasonal Variation of the Tropical Circulation as Simulated by a Global Model of the Atmosphere," J. Atmos. Sci. 31, 43.

MANGARELLA, P.A., VAN DUSEN, E.S. (1973) "Submerged Thermal Discharges from Ocean Sited Power Plants," Technical Report NSF/RANN/SE/ GI-34979/TR/73/10.

MATHUR, M.B. (1974) "A Multiple-Grid Primitive Equation Model to Simulate the Development of an Asymmetric Hurricane (Isabell, 1964)," J. Atm. Sci. 31, 371.

MELLOR, G.L., DURBIN, P.A. (1975) "The Structure and Dynamics of the Ocean Surface Mixed Layer," J. Phys. Oceanogr. 5, 718.

MELLOR, GL, YAMADA, T. (1974) "A Hierarchy of Turbulence Closure Models for Planetary Boundary Layers", J. Atmos. Sci. 31, 1791.

MILES, J. (1971) "Internal Waves Generated by a Horizontally Moving Source," Geophys. Fluid Dynam. 2, 63.

MONIN, A.S., OBUKHOV, A.M. (1954) "Basic Regularity in Turbulent Mixing in the Surface Layers of the Atmosphere," USSR Acad. Sci. Workshop Geophys. Met., No. 24, 163.

MUNK, W.H., ANDERSON, E.R. (1948),"Notes on a Theory of the Thermocline," J. Mar. Res. 7, 276.

NAMIAS, J. (1970) "Macroscale Variations in Sea-Surface Temperatures in the North Pacific," J. Geophys. Res. 75, 565.

NAMIAS, J. (1973) "Thermal Communication Between the Sea Surface and the Lower Troposphere," J. Phys. Oceanogr. 3, 373.

NEUMANN, G., PIERSON, W.J., JR. (1966) "Principles of Physical Oceanography," Prentice-Hall.

O'BRIEN, J.J., REID, R.O. (1967) "The Nonlinear Response of a Two-Layer Baroclinic Ocean to Stationary Axially Symmetric Hurricane, Part I. Upwelling Induced by Momentum Transfer," J. Atmos. Sci. 24, 197.

O'BRIEN, J.J. (1967) "The Nonlinear Response of a Two-Layer Baroclinic Ocean to a Stationary Axially Symmetric Hurricane, Part II. Upwelling and Mixing, J. Atmos. Sci. 24, 203.

O'BRIEN J.J. (1969) "A Numerical Study of the Entire Wind-Driven Pacific Ocean," Trans. A.G.U.

O'BRIEN J.J., HURLBURT, H.E. (1972) " A Numerical Model of Coastal Upwelling," J. Phys. Oceanogr. 2, 14.

OCEANOGRAPHIC OFFICE, U.S. NAVY (1967) Oceanography Atlas of the North Atlantic Ocean. Section 2. Physical Properties. U.S. Naval Oceanographic Office, Publication No. 700.

O'BRIEN, J.J., WROBLEWSKI, J.S. (1973) "A Simulation of the Mesoscale Distribution of the Lower Marine Trophic Levels off West Florida", Invest. Resq. 37, 193.

OLIGER, J.E., SUNDSTROHM, A. (1975) "Theoretical and Practical Problems in Formulating Boundary Conditions for a Limited-Area Model," (in prep.)

ORSZAG, S.A., PATTERSON, G.S. (1972a) "Numerical Simulation of Three-Dimensional Homogeneous Isotropic Turbulence", Phys. Rev. Letters 28, 76.

ORSZAG, S.A., PATTERSON, G.S. (1972b) "Numerical Simulation of Turbulence", Lecture Notes in Physics, 12, Statistical Models and Turbulence, Berlin, Springer, 127.

ORSZAG, S.A., ISRAELI, M. (1973a) "Numerical Simulation of Viscous Incompressible Flows", Report 17, Flow Research, Inc., Kent, Wash.

ORSZAG, S.A., PAO, H.-H (1973b) "Numerical Simulation of Turbulent Shear Flow", Proc. Second IUTAM-IUGG Symp. on Turbulent Diffusion in Environmental Pollution, Adv. in Geophys.

OSTAPOFF, F., WORTHEM, S. (1974) "On the Intra-Diurnal Temperature Variation in the Upper Ocean Layer," (IAMAP-IAISO Meeting Melbourne Australia, Jan. 1974). J. Phys. Oceanogr. 4, 601.

PANDOLFO, J. (1966) "Wind and Temperature Profiles," J. Atmos. Sci. 23, 495.

PHILLIPS, O.M. (1966) "The Dynamics of the Upper Ocean," Cambridge Univ. Press.

PIACSEK, S.A., ROBERTS, G.O. (1975) "Numerical Results on Collapsing Wakes in a Stratified Fluid," NRL Technical Report, to appear.

PIACSEK, S.A., WARN-VARNAS, A. (1975) "Second-Order Closure Models for Turbulence in the Presence of Stratification and Shear," (in prep).

PIKE, A.C. (1972) "Response of the Tropical Atmosphere and Ocean Model to Seasonably Variable Forcing," Mon. Weather Rev. 100, 424.

PLATT, T., DENMAN, K.L. (1975) "A General Equation for the Mesoscale Distribution of Plankton in the Sea", Proc. Sixth Liege Coll. on Ocean Hydrodynamics, Mem. Soc. Roy. Sciences Liege, in press.

POLICASTRO, A.J., TOKAR, J.V. (1972) "Heated-Effluent Dispersion in Large Lakes: State-Of-The-Art of Analytical Modeling," Report ANL/ES-11.

POLLARD, R.T., RHINES, P.B., THOMPSON, R. (1973), "The Deepening of the Wind-Mixed Layer," Geophys. Fluid Dynam. 3, 381.

RATCLIFFE, R.A.S., MURRAY, J. (1970) "New Lag Associations between North Atlantic Sea Temperature and European Pressure Applied to Long-Range Weather Forecasting," Quart. J.R. Met. Soc. 96, 226.

RAYMONT, J.E.G. (1966) "The Production of Marine Phytoplankton", Adv. Ecol. Res. 3, 117.

RILEY, G.A., STOMMEL, H., BUMPUS, D.F. (1949) "Quantitative Ecology of the Plankton of the Western North Atlantic", Bull, Bingham Oceanog. Coll. 12,(3), 1.

ROBERT, A.J., KWIZAK, M. (1971) "A Semi-Implicit Scheme for Grid Point Atmospheric Models of the Primitive Equations," Mon. Weather Rev. 99, 32.

ROBERTS, G.O. (1975) "Internal Wave Generation from a Disturbed Region", NRL Memorandum Report, to appear.

ROWNTREE, P.R. (1972) "The Influence of Tropical East Pacific Ocean Temperature on the Atmosphere," Q.J. Roy. Met. Soc. 98, 290.

SEMTNER, A.J. (1972) "A Numerical Investigation of Arctic Ocean Circulation", Trans. A.G.U. 53, 1015.

SHAPIRO, M.A., O'BRIEN, J.J. (1970) "Boundary Conditions for Fine-Mesh Limited-Area Forecasts," J. Appl. Meteor. 9, 345.

SILBERMAN, E., STEFAN, H. (1970) "Physical (Hydraulic) Modeling of Heat Dispersion in Large Lakes: A Review of the State of the Art," ANL/ES-2.

SIMPSON, J. (1969) "On Some Aspects of Sea-Air Interaction in Middle Latitudes," Deep-Sea Res. 16 Suppl., 233.

SMAGORINSKY, J. (1963) "General Circulation Experiments with the Primitive Equations, I. The Basic Experiment," Mon. Weather Rev. 91, 99.

SOMERVILLE, R.C.J., STONE, P.H., HALEM, M., HANSEN, J.E., HOGAN, J.S., DRUYAN, L.M., RUSSELL, G., LACIS, A.A., QUIRK, W.J., TENENBAUM, J. (1974) "The GISS Model of the Global Atmosphere," J. Atmos. Sci. 31, 84.

SOMERVILLE, R.C.J., STONE, P.H., LACIS, A.A., QUIRK, W.J., HANSEN, J.E. (1976a) "A Search for Short-Term Effects of Solar Variability in an Atmospheric General Circulation Model," J. Geophys. Res., in press.

SOMERVILLE, R.C.J. (1976b) "The Sensitivity of Atmospheric Circulation Models to Sea Surface Temperature," to appear in Proceedings of the NATO Advanced Study Institute on Modeling and Prediction of the Upper Layers of the Ocean, Urbino, Italy, Sept., 1975, Pergamon.

SPAR, J. (1973a) "Some Effects of Surface Anomalies in a Global GCM," Mon. Weather Rev. 101, 91.

SPAR, J. (1973b) "Transequatorial Effects on Sea-Surface Temperature Anomalies in a Global General Circulation Model," Mon. Weather Rev. 101, 554.

SPAR, J. (1973c) "Supplementary Notes on Sea-Surface Temperature Anomalies and Model-Generated Meteorological Histories," Mon. Weather Rev. 101, p. 767.

STEELE, J.H. (1959) "The Quantitative Ecology of Marine Phytoplankton," Biol. Rev. 34, 129.

STOMMEL, H. (1965) "The Gulf Stream," Cambridge University Press.

STOMMEL, H., SAUNDERS, K., SIMMONS, W.R., COOPER, J. (1969) "Observations of the Diurnal Thermocline," Deep Sea Res. 16, 269.

STUHMILLER, J.H. (1975) "On the Phenomenological Modeling of Turbulent Flow," Science Applications, Inc. Report SAI-75-587-LJ, LaJolla, California.

THOMAS, W.H. (1970) "Effect of Ammonium and Nitrate Concentration on Chlorophyll Increases in Natural Tropical Pacific Phytoplankton Populations," Limnol. Oceanogr. 15, 386.

THOMAS, W.H., DODSON, A.N. (1968) "Effects of Phosphate Concentration on Cell Division Rates and Yield of a Tropical Ocean Diatom" Biol. Bull. 134, 199.

TOKAR, J.V. (1971) "Thermal Plumes in Lakes: Compilations of Field Experience, ANL/ES-3.

TRIMBLE, L.C. (1975) "Ocean Thermal Energy Conversion Power Plant Technical and Economic Feasibility," Lockheed Missiles and Space Co., Inc. Report NSF/RANN/SE/GI-C937/FR/75/1, Sunnyvale, Calif.

TURNER, J.S. (1969) "A Note on Wind Mixing at the Seasonal Thermocline," Deep-Sea Res., Suppl. to Vol. 16, 737.

VAGER, B.G., ZILINTINKEVICH, S.S. (1968) "A Theoretical Model of the Diurnal Variations of the Meteorological Fields", Meteorol. Gidrol, 7.

VERHOFF, F.H. (1971) "Theoretical Analysis of a Conserved Nutrient Ecosystem", J. Theor. Bio. 33, 131.

VON ARX, W.S. (1962) "An Introduction to Physical Oceanography," Addison-Wesley.

WANG, H.H., HALPERN, P. (1970) "Experiments with a Regional Fine-Mesh Prediction Model," J. Appl. Meteor. 9, 545.

WASHINGTON, W.M. (1972) "Numerical Climatic-Change Experiments: The Effects of Man's Production of Thermal Energy," J. Appl. Meteor. 11, 768.

WASHINGTON, W.M., KASAHARA, A. (1970) "A January Simulation Experiment with the Two-Layer Version of the NCAR Global Circulation Model," Mon. Weather Rev. 98, 559.

WILLIAMS, G.P. (1969) "Numerical Investigation of the Three-Dimensional Navier-Stokes Equations for Incompressible Flow," J. Fluid Mech. 37, 727.

WILLIAMS, J. (1962) "Oceanography," Little, Brown, & Co.

WILLIAMS, J., BARRY, R.G., WASHINGTON, W.M. (1974) "Simulation of the Atmospheric Circulation using the NCAR Global Circulation Model with Ice Age Boundary Conditions", J. Appl. Meteor. 13 ,305.

WILLIAMSON, D.L., BROWNING, G.L., (1974) "Formulation of the Lateral Boundary Conditions for the NCAR Limited-Area Model," Jour. Appl. Meteor. 13, 8.

WROBLEWSKI, J.S., O'BRIEN, J.J. (1975) Spatial Model of Phytoplankton Patchiness", Mar. Biology, in press.

WROBLESKI, J.S., O'BRIEN, J.J., PLATT, T. (1974) "On the Physical and Biological Scales of Phytoplankton Patchiness in the Ocean," Mem. Soc. Roy. Sciences Liege 8, 43.

WYRTKI, K. (1961) "The Thermohaline Circulation in Relation to the General Circulation of the Oceans," Deep Sea Res. 8, p. 39.

YAMADA, T. (1975) "The Critical Richardson Number and the Ratio of the Eddy Transport Coefficients Obtained from a Turbulence Closure Model," J. Atmos. Sci. 32, 926.

YOSHIHARA, H. (1968) "Sea-Air Interaction: A Simplified Model," J. Atmos. Sci. 25, 729.

ZENER, C. et al. (1973a) "Solar Sea Power," Physics Today, (Jan. 1973) 48.

ZENER, C. et al. (1973b) Carnegie-Mellon University Prog Report NSF/RANN/SE/GI-349114/PR/73/1-1973 , "Solar Sea Power".

ZENER, C. et al. (1974), Carnegie-Mellon University Progress Report NSF/RANN/SE/GI-394114/PR74/2-1974 , "Solar Sea Power".

<u>OTEC Environmental Distribution List</u>

Alexiou, Arthur G.
Associate Director Programs
Office of Sea Grant/NOAA
Rockville, Md. 20852

Anderson, J. H.
Sea Solar Power, Inc.
1615 Hillock Lane
York, PA. 17403

Atwood, Donald K.
Marine Science Dept.
University of Puerto Rico
Mayaguez PR 00708

Bathen, Karl H.
Associate Professor
Dept. of Ocean Engineering
University of Hawaii
Manoa Campus
Honolulu, HI 96822

Battelle Memorial Institute
ATTN: Technical Information Section
Pacific Northwest Laboratory
P. O. Box 999
Richland, WA. 99352

Beall, Sam E.,(Jr.)
Director Energy Division
Oak Ridge National Laboratory
P. O. Box X
Oak Ridge, TN. 37806

Boller, John W.
Executive Director
Marine Board
National Academy of Engineering
2101 Constitution Avenue, N. W.
Washington, D. C. 20418

Bretschneider, Charles L.
Dept. of Ocean Engineering
University of Hawaii
2565 The Mall
Honolulu, HI 96822

Buskirk, Alden Van
AID/ENGR/SP/SP
Agency for International Development
Room 517 S A 11
Washington, D. C. 20523

Chamberlain, S. G.
Raytheon Company
P. O. Box 360
Portsmouth, RI 02871

Cohen, Robert
OTEC Program Manager
Solar Energy Division
ERDA
Washington, D. C. 20545

Coyle, Arthur J.
Batelle Laboratory
505 King Street
Columbus, OH 43281

Dexter, Stephen C.
Assistant Scientist
Woods Hole Oceanographic
Woods Hole, MA 02543

Douglas, Jr., Robert H.
Manager
Ocean and Energy Systems Project
TRW Systems
One Space Park
Redondo Beach, CA 90278

Dugger, Dr. Gordon L.
Assistant Supervisor
Aeronautics Division
The Johns Hopkins University
Applied Physics Laboratory
8621 Georgia Avenue
Silver Spring, MD 20910

Eldridge, Ralph G.
Technical Staff
The Mitre Corporation
Westgate Research Park
McLean, VA 22101

Fisher, Dr. F. H.
Associate Director
Research Oceanographer
Marine Physical Laboratory
Scripps Institute of Oceanography
San Diego, CA 92132

Griffin, Arthur B.
TRW Systems
Manager, Professional Staff
Ocean and Energy Systems Project
TRW Inc/TRW Systems
One Space Park
Redondo Beach, CA 90278

Griffith, Steve
Gilbert Associates
1828 L. Street, N. W.
Washington, D. C. 20036

Harrenstien, Howard P.
Dean
School of Engineering
University of Miami
P. O. Box 248294
Miami, FL 33124

Heronemus, William E.
Professor
Department of Civil Engineering
Marston Hall
University of Massachusetts
Amherst, MA 01002

Hirshman, Jules
Director of Special Projects
Tracor Marine
P. O. Box 13114
Pt. Everglades, FL 33316

Hollett, John
Global Marine
P. O. Box 3010
Newport Beach, CA 92663

Isaacs, John
Inst. of Marine Resources
University of Calif.
San Diego, CA 92037

Jeremia, Dr. John
M. E. Dept. 11C
U. S. Naval Academy
Annapolis, MD 21402

Jirka, Dr. Gerhard
Research Engineer
MIT 48-315
Cambridge, MA 02130

Justus, John R.
Analyst in Physical Science
CRS/SPRD
Library of Congress
10 First Street, S. E.
Washington, D. C. 20540

Lavi, Abrahim
Professor
Carnegie-Mellon University
Pittsburgh, PA 15217

Lehman, Richard
U. S. Department of Commerce
Main Commerce Building
Room 5315
Washington, D. C. 20230

Lewis, Lloyd
Chesapeake Division (Code FPO-1SP)
Naval Facilities
Engineering Command
Washington Navy Yard
Washington, D. C. 20374

Little, Dr. Thomas E.
Oceanic Division
Westinghouse Electric Corporation
P. O. Box 1488
Annapolis, MD 21404

Livingston, Richard
PM 221
401 M St., S. W.
U. S. Environmental Protection Agency
Washington, D. C. 20460

Lutkefeder, Norman
Federal Energy Administration
12th and Pennsylvania Ave., N. W.
Washington, D. C. 20161

Mangarella, Peter A.
Assistant Professor
University of Massachusetts
Amherst, MA 01002

Manikowski, A. F.
Dept. 57-22
Building 150
Lockheed MSC
Sunnyvale, CA 94088

McCluney, Ross
Florida Solar Energy Research Center
Cape Canaveral, FL. 32920

McCormack, Professor
U. S. Naval Academy
Annapolis, MD. 21402

Naef, Frederick E.
Lockheed Missiles and Space Co.
900 Seventeenth St., N. W.
Washington, D. C. 20006

New, Dr. R.
6001 Executive Blvd. (C61)
Rockville, Md. 20852

O/Brien, Dr. James J.
Department of Meteorology
Florida State University
Tallahassee, Fla. 32306

Paskausky, David F.
Professor
Marint Sciences Institute
University of Connecticut
Groton Ct. 63040

Pauli, Denzil
Marine Board, NRC,
2101 Constitution Ave., N. W.
Washington, D. C. 20418

Perhac, Dr. Ralph M.
Program Manager
Division of Advanced Environmental
Research and Technology
National Science Foundation
Room 1132
1800 G Street
Washington, D. C. 20550

Pujes, Jean
French Scientific Mission
2011 Eye Street, N. W.
Washington, D. C. 20006

Roels, Oswald A.
University of Texas
Marine Sciences Inst.
Port Aransas, TX 78373

Rooth, Claes G. H.
RSMAS
University of Miami
10 Rickenbacker Causeway
Miami, Fl. 33149

Sackett, Professor William
Department of Oceanography
Texas A and M University
College Station, TX 77843

Satkowski, John A.
Acting Director
Power Program
Office of Naval Research
800 North Quincy Street
Arlington, Va. 22217

Silva, E. A.
Naval Facilities Engineering Commission
200 Stovall Street
Alexandria, VA 22332

Skowbo, Dr. H.
U. S. Energy Research and Development Administration
Solar Energy Division
20 Massachusetts Ave., N. W.
Washington, D. C. 20545

Spuhler, Harold A.
Program Manager
OTEC
National Science Foundation
1800 G Street, N. W.
Washington, D. C. 20550

Stewart, Harris B.
NOAA/AOML
15 Rickenbacker Causeway
Miami, FL 33149

Sundaram, Dr. J.
Hydronautics, Inc.
7210 Pindell School Road
Laurel, Md. 20810

Super, Tom
Energy and Environmental Analysis
1701 N. St. Meyer Drive
Ste. 1211
Arlington, VA 22209

Trimble, Lloyd C.
Program Manager
Ocean Energy Systems
Lockheed Missiles and Space Co., Inc.
P. O. Box 504
Sunnyvale, CA 94088

Wolff, Paul M.
Vice President
Oceanographer
Ocean Data Systems, Inc.
2400 Garden Road
Monterey, CA 93940

Zener, Clarence
Professor
Carnegie- Mellon University
Schenley Park
Pittsburgh, PA 15213

U. S. Congress
Office of Technology Assessment
Washington, D. C. 20510

Division of Solar Energy
U. S. Energy Research and Development Administration
Washington, D. C. 20545
ATTN: Director
ATTN: Deputy Director
ATTN: Director, Projects Branch
ATTN: Assistant Director for Solar Electric Application
ATTN: Contracts Branch

U. S. Energy Research and Development Administration
Division of Reactor Research and Development
Auxiliary Projects Branch
Washington, D. C. 20545

U. S. Energy Research and Development Administration
Solar, Geothermal and Advanced Energy Systems
Washington, D. C. 20545

Technical Information Center
U. S. Energy Research and Development Administration
P. O. Box 62
Oak Ridge, TN 37830

ERDA Library
U. S. Energy Research and Development Administration
Mail Station G-043
Washington, D. C. 20545

ATTN: Assistant for Energy Resources
Office of the Secretary of Defense
Room 1D760
The Pentagon
Washington, D. C. 20301

ATTN: Library Code-2124
Superintendent
Naval Postgraduate School
Monterey, CA 93940

ATTN: Director
Naval Energy R and D Office
NSRDC Annapolis Laboratory
Annapolis, MD 21402

ATTN: Director
Naval Research Laboratory
Washington, D. C. 20375
ATTN: Code 7700, Dr. Coffey 25 copies

Code 7750, Dr. Boris 150 copies

ATTN: Library
National Academy of Sciences
2101 Constitution Avenue
Washington, D. C. 20418